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FINAL REPORT

on

CHARACTERIZATION OF BCL STRAIN GAGES FOR USE TO 1366 K (2000 F)

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

August 27, 1975

by

M. M. Lemcoe

Contract NAS1-13357

Langley Research Center
Hampton, Virginia

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ABSTRACT

In this program, further characterization studies were conducted on BCL strain gage behavior under static and transient heating conditions at rates up to 2.78 K/sec (5 F/sec) and temperatures up to 1366 K (2000 F). In addition, more optimum time-temperature parameters were developed for preconditioning (prestabilizing) BCL gages. A limited study was carried out to determine the extent of spalling of the platinum cladding during fabrication of platinum-clad wire strain gages. Further verification was also carried out on the convergence and repeatability of the apparent strain characteristics of the BCL gage under heating and cooling cycles. The significance of these characteristics from the standpoint of enhancing measurement accuracy is also discussed.

It is concluded that the BCL gage should perform satisfactorily to temperatures approaching 1366 K (2000 F). This report should be of particular interest to those involved in strain measurement above 783 K (950 F) or in verification of safety and in-service performance of equipment and systems germane to the aerospace and energy-related industries.

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CHARACTERIZATION OF BCL STRAIN GAGES FOR USE TO 1366 K (2000 F)

by

M. M. Lemcoe

BATTELLE-COLUMBUS LABORATORIES

SUMMARY

Under prior NASA Langley contracts, a high-temperature electric resistance strain gage system was developed for use to temperatures approaching 1366 K (2000 F). A strain gage alloy (Fe-25Cr-7.5Al), also developed at the Battelle-Columbus Laboratories, was used to fabricate the gage which hereinafter is referred to as the BCL gage. Gages with this temperature capability are required to determine stresses (or strains) during flight, or to provide a check on accuracy of analytical predictions used to design high-temperature structures. Commercially available electric resistance strain gages have an upper temperature limit for static measurements of approximately 783 K (950 F), which is not adequate for the applications in question.

This program effort was primarily devoted to (a) the development of more optimum time-temperature combinations for preconditioning (prestabilization) BCL gages, (b) further characterization of BCL gage behavior under static heating conditions, and (c) characterization of BCL gage behavior under transient heating conditions at heating rates up to 2.78 K/sec (5 F/sec). In addition, a limited study was carried out on the feasibility of fabricating BCL platinum-clad gages without excessive spalling of the platinum cladding during gage winding. In the previous program, it was demonstrated that it is possible to platinum-clad BCL wire by means of the sputtering process, and that it is possible to achieve varying degrees of temperature compensation of the wire by controlling the thickness of the cladding. Effort was also devoted to further verification of the BCL gage

repeatability characteristics, upon cooling and subsequent heating. This characteristic provides a viable means of enhancing the accuracy of high-temperature strain measurement--particularly in the temperature range of 644 K (700 F) to 1366 K (2000 F).

Basic gage characteristics were established in terms of gage factor (strain sensitivity and linearity), apparent strain under static and transient heating conditions, drift, zero-shift, gage-to-gage, and cycle-to-cycle variations. This report presents, in graphical and tabular form, results of the characterization study, curves for selection of the appropriate time-temperature combination to precondition the gage, additional pertinent information relating to further verification of the BCL repeatability characteristic during cool-down and heat-up, and to feasibility of fabricating BCL platinum-clad gages without excessive spalling.

It is concluded that, on the basis of the results from this program, and the supporting information obtained under Contract NAS1-12099, the BCL strain gage system herein described should perform satisfactorily up to temperatures approaching 1366 K (2000 F), under static conditions and transient heating rates of at least 2.78 K/sec (5 F/sec).

This report should be of particular interest to those involved in strain measurement at temperatures exceeding 783 K (950 F), in such applications as verification of structural integrity, or in-service surveillance of strains on high-temperature structures, or equipment germane to the aerospace and energy-related industries.

INTRODUCTION

To obtain experimental data on the magnitudes of stresses (or strains) during flight, and to provide a check on the reliability of existing analytical methods for predicting these stresses, strain gage systems with operating temperatures in excess of 1033 K (1400 F) are essential. Further, monitoring of strains during each flight provides data for assessing cyclic

or cumulative effects or remaining service life of the vehicle. These systems must, of course, be capable of field installation in remote locations on the vehicle, capable of faithfully recording strains under both static and transient conditions (including shock and vibration), be relatively insensitive to moisture, electric or magnetic fields, and not prohibitive, costwise, for strain measurements involving gages at a number of locations, which is frequently the case on space or aircraft vehicles.

Although there are commercially available electric resistance strain gages for reliable use to about 783 K (950 F), there are none that would meet the substantially higher temperature requirements.

Under prior NASA programs (See References 1 and 2) a strain gage system was developed for use to temperatures approaching 1366 K (2000 F). However, because of excessive yielding of the calibration bars at the higher temperatures, only a limited amount of gage factor (strain sensitivity and linearity) data was obtained at these temperatures. Further, because of the conventional heating system utilized (split furnace), only static apparent strain data was obtained. Also, because of the relatively low heating rates achievable with the split furnace, determination of more optimum prestabilization time-temperature combinations was not possible.

The major thrust in this program was, therefore, directed toward (a) obtaining additional gage factor information at the higher temperatures, (b) generating transient apparent strain information over a range in heating rates up to 2.78 K/sec (5 F/sec), and (c) further optimization of the prestabilization procedure with respect to stability (drift characteristics) and remaining gage life. To accomplish this, it was necessary to redesign the calibration and heating systems, and to utilize a multichannel data acquisition system capable of recording transient strain and temperature data. Further verification of the repeatability characteristics of the BCL gage during cool-down and heat-up was also carried out, as well as a limited study on the feasibility of fabricating platinum-clad BCL gages without excessive spalling. (Refer to Reference 1 for information on the clad-wire gage concept).

This report contains the pertinent program results and describes means of enhancing strain measurement accuracy.

EXPERIMENTAL DEVELOPMENT, EVALUATION, AND RESULTS

1. Gage Fabrication and Specimen Preparation

1.1 General

The BCL gages evaluated in this program are identical to the BCL-3 gages described in Section 1.3 of Reference 2. The gages have a nominal resistance of 70 ohms and a gage length of 20.32 mm (0.8 in) and were fabricated from a special alloy (Fe-25Cr-7.5Al) developed at Battelle for high-temperature strain gages. Unless otherwise noted herein, the materials and procedures used for the gages, lead wire, and gage attachment are those described in detail in Sections 1.2 and 1.3 of Reference 2.

1.2 Specimen Materials

1.2.1 Prestabilization Study Specimens

These specimens were fabricated from 2.84 mm (.112 in.) thick Haynes 25 alloy sheet (Heat No 1860-2-1214) having the following chemical and room temperature mechanical properties:

Cr	W	Ni	Fe	Mn	Si	C	Co
19.90	14.40	10.10	2.05	1.45	.17	.10	Balance

Tensile Strength - 1006.52 MPa (146,000 psi)

Yield Strength (.2%) - 479.13 MPa (69,500 psi)

Elongation in 50.8 mm (2 in.) - 9.0%

These specimens are identified with a "PS" prefix.

1.2.2 Gage Evaluation Specimens

Unless otherwise noted, all gage evaluation specimens were machined from IN 100 castings (Heat No. FM 4093) having the following chemical and mechanical properties:

Cr	W	Ni	Fe	Mn	Si	C	Co
14.42	8.96	5.37	4.85	3.12	0.78	.17	Balance

Tensile Strength - 916.90 MPa (133,000 psi)

Yield Strength (.2%) - 737.66 MPa (107,000 psi)

Elongation in 50.8 mm (2 in) - 9.0%

These specimens are identified with an "IN" prefix.

1.3 Specimen Geometry and Specimen Preparation

1.3.1 Prestabilization Specimens

These specimens were machined to the geometry shown in Figure 1. This geometry was dictated by the cross-sectional area required for direct resistance heating and the specimen shank size required for attachment of the water-cooled electrical clamps.

Each specimen was instrumented with 3 longitudinal BCL-3 strain gages, which were attached to the specimen on the same face. On the opposite face of the specimen, 3 Type K thermocouples were spotwelded at locations corresponding to the center and ends of the middle gage. Prior to Rokiding gages to the specimens, a graded precoat system was applied to insure adequate bond. For a detailed description of the precoat and Rokide process used to attach the gage, refer to Sections 1.4.2.3 and 1.4.3 of Reference 2.

1.3.2 Gage Evaluation Specimens

In the previous program, the calibration bar was fabricated from Haynes 25 alloy (see Figure 2, Reference 2 for bar geometry). At the higher

temperatures, the bars yielded excessively, making it difficult to obtain accurate strain sensitivity and linearity data. Also, because of their tapered geometry, these bars were inherently unsuitable for direct resistance heating. As a consequence, a complete redesign of this calibration bar was necessary. A review of commercially available wrought and cast alloys indicated that none of the wrought alloys, including Haynes 25 , had sufficient yield strengths to preclude yielding at the higher strain levels--at temperatures above 1255 K (1800 F). It was thus concluded that a cast alloy would be required. The following is a listing of the cast alloys that were considered as possible candidates:

Alloy 713LC	B-1900
GMR 235-D	X-40
Alloy 713C	TRW 1900
IN 100	UDIMET 500
Nicrotung	MAR-M246
MAR-M200	WI-52
MAR-M302	IN-162

At 1366 K (2000 F), the above cast alloys having the highest yield strengths were IN 100, B-1900, and MAR-M302. Their yield strengths were reported to be 241.29 MPa (35 ksi), 193.03 MPa (28 ksi) and 151.67 MPa (22 ksi), respectively. On the other hand, the best wrought alloy had a yield strength at 1366 K (2000 F) of only 130.99 MPa (19 ksi), with even poorer relative strength at the lower temperatures. These values were obtained from Reference 3 and, on the basis of the above ranking, IN 100 was selected as the alloy for the calibration bar.

To insure uniform temperature along the length of the calibration bar, under direct resistance heating, the calibration bar was designed as a constant cross-section cantilever beam (the calibration bar used in the previous program was a "constant stress"(or strain) type cantilever beam). To provide sufficient gripping area for the loading of fixture and the water-cooled electrical clamps, the specimen ends were enlarged. Figure 2 shows the specimen geometry, gage, and thermocouple locations.

The calibration bar was sized to readily accomodate at least 8 BCL-3 gages. Upon completion of specimen design, several sources--specializing in high-temperature castings--were contacted, and an order was placed with TRW, Inc., Minerva, Ohio,for two IN 100 cast specimens. The specimens were cast slightly oversize and finish-machined and ground at Battelle.

1.3.3 Calibration Specimens

Specimen IN-1 was instrumented with Micromeasurements EA-09-125AD-120 gages which were distributed along both faces at the same general locations as gages that would later be applied on Specimen IN-2. This specimen was used to permit accurate calibration of the loading system at room temperature. Specimen IN-1 was then instrumented with 7 Type K thermocouples to check temperature distribution along the entire length of the test section, when subjected to direct resistance heating. Refer to Figure 2 for gage and thermocouple locations.

2. Description of Equipment and Facilities

2.1 Equipment for Prestabilization Study

Heat energy for prestabilization was provided by an electrical heating system comprised of a 10 kva, multi-tap, step-down power transformer and temperature programmer (Research, Inc. Model FGE 5110 Datatrak), and power controller (Research, Inc. Model SPR-240/140-CLA-E Phaser). This system was capable of heating the specimens to their required temperatures at heating rates in excess of 28 K/sec (50 F/sec and maintained temperature within ≠ 1.1 K (2 F).

A Vidar multichannel data acquisition system was used to record temperature vs time at 6 points on a dummy specimen during several trial runs to establish the proper power settings. Power from the heating system was delivered into the specimen through water-cooled high-current cables which were attached to each end of the specimen by means of water-cooled copper clamps.

During the prestabilization study, a portable Vishay strain indicator, switch and balance unit, and precision potentiometer were used to measure strain and temperature.

2.2 High-Temperature Strain Gage Evaluation Facility

This facility is as described in detail in Section 2.1 of Reference 2, except for the transient heating system and the Vidar multichannel data acquisition system, which were incorporated during this program. Figure 3 is an overall view of the present facility. The split furnace, which was used for some of the static evaluations, is not shown. It was generally removed, prior to commencement of a transient heating evaluation. Figure 4 is a close-up view of the loading system with an instrumented specimen in place. The water-cooled electrical cables and clamps are shown attached to the specimen and dc power supply.

The transient heating system is comprised of (a) an 18 kw, dc power supply, with a saturable reactor which can deliver 75 to 1500 amperes at maximum tap voltage of 0.1, 3, 6, 9, and 12 volts, with a response time of 200 ms from minimum to maximum output, at a specified ripple not to exceed 5 percent, (b) Research, Inc. Model D-30 Thermac temperature controller, and (c) buffer amplifier.

The Vidar data acquisition system,which incorporates an integrating digital voltmeter and digital clock, can accommodate up to 100 channels of strain gages or thermocouples and scan at a rate of 20 channels per second. The gage or thermocouple output is indicated on the digital voltmeter and recorded on printed paper tape. To use this system, it was necessary to fabricate bridge completion modules to permit simultaneous evaluation of up to 8 strain gages.

3. Prestabilization Study

Each of the 4 Haynes 25 prestabilization specimens, described in Section 1.3.1, was prestabilized at a different temperature for varying periods

of time in the direct resistance heating facility described in Section 2.1. The temperatures were as follows:

Specimen	Temperature K, (F)		Time to reach temperature, Min.	Total Prestabilization time, Min.
PS-2-1	1366 K	(2000 F)	38	154
PS-3	1311 K	(1900 F)	40	135
PS-4	1255 K	(1800 F)	45	150
PS-5	1200 K	(1700 F)	47	120

Drift was monitored as a function of time, after reaching the set-point temperature. The soak was continued until the drift rate became essentially constant. It was felt that any small improvement in gage stability (decrease in drift rate) that might occur after that time would not be justified in terms of possible gage degradation or reduction in remaining gage life.

After determination of the stability characteristics in terms of drift rate, the apparent strain vs temperature characteristics of the gages on Specimens PS-2-1 and PS-3 were determined in the same facility, at 1311 K (1900 F) and 1366 K (2000 F). This was done to determine, as early as possible in the program, the differences in apparent strain resulting from the shorter prestabilization times arrived at on the basis of drift rate. The prestabilization procedure would have been altered at this point in the program, if apparent strain characteristics had been adversely affected--which was not the case. It should be noted that in the previous program, gages were generally prestabilized for 4 hours.

Refer to Section 7.1 for results.

4. Gage Characterization Study

4.1 Calibration of Loading System and Check on Uniformity of Specimen Temperature.

Prior to commencement of the gage characterization study, the loading system was calibrated with Specimen IN-1, which is described in

Section 1.3.3. Calibration was performed at room temperature by applying known deflections and accurately measuring the strains, (in tension and compression) to 2000 $\mu\varepsilon$ at 3 spanwise locations within the test section, with the 8 strain gages. It should be noted that a room temperature calibration also provides calibration at elevated temperatures--if the temperature is uniform throughout the stressed portion of the calibration bar.

4.2 Static and Transient Gage Characteristics.

Upon completion of the calibration, a check on the uniformity of temperature distribution was made at 7 points within the test section of the same specimen, while the specimen was subjected to direct resistance heating. Thermocouple readings were taken at 700 K (800 F) for 922 K (1200 F), and 1144 K (1600 F). Refer to Section 7.2.1 for results.

Specimen IN-2 was prestabilized at 1325 K (1925 F) for approximately 2 hours. This time period was selected on the basis of the results from the optimum prestabilization study described in Section 7.1. After completion of the prestabilization, the specimen was then subjected to three thermal precycles to 1325 K (1925 F) and three mechanical precycles to approximately 2000 $\mu\varepsilon$ while at 1325 K (1925 F).

Subsequent to completion of the gage preconditioning, their apparent strain characteristics to 1311 K (1900 F) were determined under static and transient heating conditions. The first of the three static evaluation cycles was performed with manual strain and temperature readout equipment. This was done to expedite establishing the set points for the Data Trak temperature programmer which provided the desired time-temperature history for Cycles 2 and 3. The apparent strain and temperature for these last two cycles and all subsequent transient apparent strain evaluations were automatically recorded with the Vidar Data acquisition system. The transient apparent strain vs temperature characteristics were determined by subjecting the gages to 3 consecutive cycles to 1311 K (1900 F) at each of the 3 heating rates of 0.55 K/sec (1 F/sec), 1.67 K/sec (3 F/sec), and 2.78 K/sec (5 F/sec).

Upon completion of the apparent strain characteristization, the drift characteristics were determined at 1311 K (1900 F) and recorded on the Vidar.

Finally, the gage factor characteristics at room temperature, 922 K (1200 F), and 1311 K (1900 F) were determined at maximum strain levels ranging from 1000 $\mu\varepsilon$ to 1500 $\mu\varepsilon$ in the calibration bar. At the outset of this program, it was hoped that the gage factor evaluation could be performed to 2000 $\mu\varepsilon$ at all temperatures. However, this was not possible due to yielding in the calibration bar. It was, therefore, decided to postpone gage factor evaluations until after completion of all evaluations utilizing direct resistance heating. An earlier attempt indicated that it was not feasible to utilize direct resistance heating to determine gage factor characteristics at elevated temperatures, because of calibration errors resulting from the reduction in temperature in the immediate vicinity of the specimen end clamps. It was found that this reduction in temperature sufficiently increased the effective stiffness of the specimen in the immediate vicinity of the clamp to affect the overall accuracy of calibration of the loading system. As mentioned in Section 4.1, the room temperature calibration is valid at elevated temperatures only if temperature is uniform from the loading mandrel to the point of contact with the end clamps. As a consequence, the split furnace was reinstalled in the facility and utilized during the determination of gage factor characteristics at elevated temperature.

5. Verification of Repeatability of Apparent Strain During Cool-Down

After completion of the prestabilization study described in Section 3, Specimens PS-2-1 and PS-3 were utilized to verify that the apparent strain characteristics during cool-down and subsequent heat-up are repeatable. Apparent strain vs temperature data were obtained to maximum temperatures of 1311 K (1900 F) on Specimen PS-3 and 1366 K (2000 F) for the 3 gages on each of Specimens PS-3 and PS-2-1, respectively. Refer to Section 7.3 for results.

6. Sputter-Clad BCL-3 Gages

In the previous program, it was clearly demonstrated that the sputtering technique can be effectively utilized to deposit a platinum cladding on BCL-3 wire. It was also demonstrated that platinum cladding of the proper thickness offers a viable way to temperature compensate BCL-3 wire. (Refer to Reference 2 for further details) To determine if it is feasible to fabricate gages from platinum-clad BCL-3 wire without excessive spalling of the cladding, two gages were fabricated from a limited quantity of BCL-3 wire that was platinum-clad at NASA Langley by means of the sputtering process. During fabrication of the gages in the strain gage winding fixture, the wire was closely observed to determine the extent to which the cladding might spall while making the 180^o bends around the 0.33 mm (.0132 in.) dia pins of the winding fixture. The gages , along with two standard BCL-3 gages, were then installed on Specimen H-33, which was a Haynes 25 evaluation specimen from the previous NASA program. Although it was not possible to strongly bond the Rokide to the old precoat to the degree desired, there was sufficient bond to obtain some information on apparent strain after prestabilization of the gages at 1925 F.

Refer to Section 7.4 for results.

7. Results

7.1 Prestabilization Study

Figure 5 is a plot of drift versus prestabilization time at temperature for Haynes 25 Specimens PS-2-1, PS-3, PS-4, and PS-5. Each curve represents the average of 3 gages. It is noted that, for time periods less than about 50 minutes, the drift rate is nonuniform and relatively large, and does not "level out" or become uniform until after about 1 hour--regardless of the prestabilization temperature. Further, there appears to be no further reduction in drift rate after 2 hours of prestabilization at 1900 F. Likewise, it is noted that 1 hour of prestabilization at 1900 F is equivalent to 2 hours of prestabilization at 1700 or 1800 F, in terms of instantaneous drift rate.

Figures 6 through 9 are plots of apparent strain versus temperature for gages on Haynes 25 Specimen PS-2-1 and PS-3. The data from which these plots were made were obtained after prestabilization. Referring to these figures, it is noted that the maximum absolute values of apparent strains are substantially less than reported in Reference 2 for similar gages that were prestabilized for 4 hours. For example, referring to Figures 12 and 13 in referenced report, the apparent strains vary from about -5000 $\mu\varepsilon$ to +40,000 $\mu\varepsilon$. This compares with a maximum of -9400 $\mu\varepsilon$ for gages prestabilized for the periods (less than 2.6 hours.) This corresponds to nearly a 5 to 1 reduction in apparent strain range.

7.2 Gage Characterization Study

7.2.1 Calibration of Loading System and Check on Uniformity of Specimen Temperature.

The specimen described in Section 1.3.3 and calibration procedure described in Section 4.1 were used to calibrate the loading system of the high-temperature strain gage evaluation facility. Figure 10 is a plot of dial gage deflective vs induced strains for gages on both faces of the calibration bar at a location 16.24 cm (6.3925 in.) from the loading mandrel. It is noted that the response is linear up to 2000 $\mu\varepsilon$ in both tension and compression, with virtually no difference between tensile or compressive readings. For example, at maximum deflection, the tensile and compressive induced strains were 1978.5 $\mu\varepsilon$ and - 1981.0 $\mu\varepsilon$, respectively. From the gages at these locations and the gages at two other locations within the test section, it was possible to accurately determine the strain distribution at any point within the test section. It was verified that the strain did vary linearly along the entire test section--in accordance with theory.

After completion of the calibration, the specimen uniformity of temperature was checked at 700 K (800 F, 922 K (1200 F), and 1144 K (1600 F) as described in Section 4.1. Table 1 is a summary of temperature readings over the test section within which the 8 strain gages are located. On the basis of these readings, it was decided that this degree of uniformity in temperature would prove to be satisfactory at all temperatures.

TABLE 1. CALIBRATION BAR TEMPERATURE DISTRIBUTION

	Readings at Nominal Temperature of		
Thermocouple	700 K (800 F)	922 K (1200 F)	1144 K (1600 F)
2	702.04 K (804 F)	908.15 K (1175 F)	1145.37 K (1602 F)
3	700.92 K (802 F)	916.48 K (1190 F)	1130.37 K (1575 F)
4	700.37 K (801 F)	922.04 K (1200 F)	1141.48 K (1595 F)
5	704.26 K (808 F)	927.59 K (1210 F)	1149.82 K (1610 F)
6	703.70 K (807 F)	925.37 K (1206 F)	1152.59 K (1615 F)
Mean Temp =	702.26 K (804.4 F)	919.93F (1196.2 F)	1143.93 K (1599.4 F)

7.2.2 Static and Transient Gage Characteristics

7.2.2.1 General

The results of the gage characterization study are presented herein, in terms of gage factor and linearity, apparent strain, drift, zero-shift. Unless otherwise stated, the above characteristics were obtained for a gage factor setting of 2.00. The true value of strain for any other gage factor may be readily obtained from the relation

$$\varepsilon_T = \varepsilon_M \frac{GFS}{GF}$$

where

ε_M = measured strain for a gage factor setting (GFS) = 2.00

GF = true gage factor obtained from gage factor versus temperature curve or other information.

7.2.2.2 Gage Sensitivity and Linearity

Figures 11, 12, and 13 are plots of true strain vs measured strain at room temperature, 922 K (1200 F), and 1311 K (1900 F) for the gages on Specimen IN-2. The plots were constructed by fairing straight lines through as many points as possible.

Referring to Figure 11, it is noted that (a) the room temperature response is quite linear to the maximum strain level, (b) the strain response for gages 7 and 8 was somewhat less than that for Gage 1, and (c) the strain response in tension is slightly greater than in compression. A rerun for gages 7 and 8 gave almost identical response to the first run.

Figure 12 is a similar plot at 922 K (1200 F). It is noted that (a) the response is reasonably linear, (b) the strain response in tension is essentially the same as that in compression, and (c) there is the usual reduction in strain sensitivity with temperature as evident from a comparison of Figures 11 and 12.

Figure 13 is a similar plot at 1311 K (1900 F). The behavior is similar to that at room temperature, except for the strain sensitivity which, of course, should be less because of the higher temperature.

Table 2 is a summary of the gage factors, in tension and compression, which were computed from the slopes of the plots in Figures 11, 12, and 13. They were computed at a true strain of 1000 $\mu\varepsilon$ from the equation presented in Section 7.2.2.1. It should be mentioned that the average value of measured strain (at 1000 $\mu\varepsilon$ true strain) was used, in each instance, in computing the gage factor. Also contained in Table 2 for comparison purposes, are the gage factors obtained from the previous NASA programs. It is noted that the correlation is, in general, good.

7.2.2.3 Zero Shift Characteristics

Table 3 is a summary of the zero-shifts which were observed during the determination of gage strain sensitivity and linearity characteristics. It is observed that (a) with the exception of the first cycle zero-shifts, the shifts are, in general, small, the third cycle zero-shifts generally being the smallest, (b) there seems to be no strong correlation between temperature and the magnitude of the zero-shift, (c) the largest zero-shifts tend to occur at the highest strain level, under either tensile or compressive loadings.

The three largest zero-shifts were +184, -168, +160 $\mu\varepsilon$, all occurring at the 1500 $\mu\varepsilon$. The question naturally arises as to whether these zero-shifts are due to yielding or other effects in the IN 100 calibration bar, or due to effects related to the gage system itself.

Zero-shift, which is defined as the change in gage reading after removal of the mechanical loading (or after application of a thermal cycle), is due to any one or a combination of the following three effects:

(1) Hysteresis or permanent deformation in the material to which the gage is attached, resulting from application and removal of a mechanical loading

(2) Dimensional change in material to which gage is attached due to thermal cycling, in the absence of mechanical load

TABLE 2. GAGE FACTOR SUMMARY

Contract	Room Temperature Tension	Room Temperature Compression	922 K (1200 F) Tension	922 K (1200 F) Compression	1311 K (1900 F) Tension	1311 K (1900 F) Compression
NAS1-11277	2.62	2.29	2.05	2.02	---	---
NAS1-12099	2.47	2.53	1.84	1.90	1.59	1.53
NAS1-13357	2.40	2.28	1.90	1.95	1.46	1.43

TABLE 3. SUMMARY OF ZERO-SHIFTS

Gage No.	Temperature K	Temperature F	Strain Level, με	Cycle No.	Zero-Shift, με Under Tension	Zero-Shift, με Under Compression
1	R.T.		1000	1	+8	+124
				2	+8	+8
				3	0	+8
7	R.T.		1000	1	-16	+80
				2	+8	+8
				3	-12	0
8	R.T.		1000	1	0	+36
				2	+4	+8
				3	+8	+4
1	922	1200	1000	1	-64	+40
				2	-4	+28
				3	+4	-32
7	922	1200	1000	1	-	-
				2	-	-
				3	-	-
8	922	1200	1000	1	-25	+24
				2	-8	+7
				3	-4	+2
1	1311	1900	1000	1	-4	+4
				2	+100	+16
				3	+4	-16
7	1311	1900	1000	1	-40	+64
				2	+12	+24
				3	-4	-8
8	1311	1900	1000	1	+8	+60
				2	-16	+8
				3	+4	+12
7	R.T.		1500	1	-44	+184
				2	+24	+12
				3	-72	+12
8	R.T.		1500	1	-16	+100
				2	+20	+20
				3	-68	+4
7	1311	1900	1500	1	-168	+160
				2	+56	+56
				3	+20	+36
8	1311	1900	1500	1	-76	+128
				2	+16	+40
				3	+48	+28

(3) A change in gage reading due to resistivity or dimensional changes in the gage system (gage, Rokide, precoat, lead tabs, leadwire, joints, etc.

An analysis of the data generated during gage precycling and evaluation and materials information on IN-100 cast material showed that the zero-shifts observed during this study stemmed from all three of the above effects.

The zero-shifts resulting from the permanent deformation induced, while cycling the 8 BCL-3 gages on Specimen IN-2 to strain levels as high as 2000 $\mu\epsilon$, are shown in the following tabulation:

Gage	Gage Zero-Shifts Cycle 1	Cycle 2	Cycle 3
1	-83	-16	-17
2	-95	-22	-19
3	+61	-14	-11
4	-49	-14	-13
5	-37	-16	-18
6	-43	-16	-18
7	+4	-16	-13
8	+1	-16	-15
Permanent Set in Specimen =	.345 mm (.0136 in.)	.010 mm (.0004 in.)	0

It is evident that a large percentage of the zero-shifts that occurred after first cycle unloading can be attributed to the permanent deformation in the specimen itself. It should be noted that the above permanent sets of 0.345 mm and 0.010 mm are 6.8% and 0.2%, respectively, of the specimen deflection required to induce 1000 $\mu\epsilon$ in Gages 1, 2, 3, and 4. The zero-shifts associated with actual changes in the gage system are considered small and are best depicted by the values tabulated for Cycle 3. It is not known why there was an increase in zero-shift for Gages 7 and 8 after the first cycle. In any event, the final zero-shifts for these two gages were comparable to the other gages.

The above clearly shows the benefits derived from precycling--in terms of preconditioning both the base material and gage system. Unfortunately, these benefits would be reduced, if the stress levels and temperatures are such that the proportional limit at temperature is exceeded at any time after precycling.

To determine the amount of dimensional change that can take place in the base material itself, due to thermal cycling, a 50.8 mm (2 in.) long cylindrical IN-100 specimen was subjected to two thermal cycles from room temperature to

1273 K (1832 F) and the percent change in specimen length upon heating and cooling determined with a dilatometer. The results are shown in Figure 14. It is noted that the curve is smooth over the entire heating and cooling portions of the loop--indicating no observable metallurgical phase changes or transformations over this span in temperature. However, it is noted that (a) the loop did not close on the first cycle, by approximately 340 microstrain--an amount actually somewhat larger than the zero shifts shown in Table 3, and (b) it took only one additional cycle to eliminate the zero shift. This graphically illustrates the importance of thermal precycling in gage preconditioning, and clearly shows that some of the gage observed zero-shift due to actual changes in the room temperature dimensions of the calibration bar. To restore the bar to its original length, at least 2 thermal cycles were required. This would not, unfortunately, eliminate subsequent dimensional changes, if the maximum thermal precycling temperature were exceeded.

7.2.2.4 Apparent Strain Characteristics

Figures 15 through 18 are plots of static apparent strain, and transient apparent strain at heating rates of 0.55 K/sec (1 F/sec), 1.67 K/sec (3 F/sec) and 2.78 K/sec (5 F/sec). They represent apparent strains to 1311 K (1900 F), nominal temperature. The static apparent strain plot was obtained at a very slow heating rate of 0.08 K/sec (0.15 F/sec). These plots show the heating up portion for each cycle and the "return to zero" point, after cooling down to room temperature.

It is noted that (a) the cycle-to-cycle variations and corresponding zero-shifts at room temperature become progressively smaller with increasing heating rate, (b) there is a progressive increase in apparent strain with increasing heating rate varying from about 19,200 $\mu\epsilon$ under static heating to about 26,400 $\mu\epsilon$ at a heating rate of 2.78 K/sec (5 F/sec), and (c) the curves characteristically converge at the maximum temperature. The importance of the convergence characteristic with respect to enhancement of measurement accuracy is discussed in Section 7.3.

The following is a tabulation of the cycle-to-cycle zero-shifts observed after cool-down from maximum temperature to room temperature.

Cycle	Static	0.55 K/sec (1 F/sec)	1.67 K/sec (3 F/sec)	2.78 K/sec (5 F/sec)
1 to 2	-745	-604	-304	-126
2 to 3	-1455	-396	-230	-76

It is clear that there is a very significant reduction in zero-shift with increasing heating rate. In applications where the heating rate is 2.78 K/sec (5 F/sec), or higher, the zero-shifts and cycle-to-cycle variations should be so small that substantially more accurate strain measurements may be possible, even without utilizing the retraceability and convergence characteristic. This finding should be of particular significance in those aerospace, missile, and atomic energy applications where heating rates of this magnitude are encountered.

It should be pointed out that the above zero-shifts are only in part due to changes within the gage system, itself. As mentioned in Section 7.2.2.3, a portion of the zero-shift is due to dimensional changes in the base material to which the gage is attached. The IN-100 material, from which the calibration specimen was fabricated, was found to have a first thermal cycle zero-shift of approximately 340 $\mu\epsilon$. Further, a zero-shift introduces an error in strain measurement only to the extent of uncertainty in predicting or establishing the amount of zero-shift occurring under thermal (or mechanical) cycling. Consequently, if the raw data is corrected for the zero-shift, the error in strain measurement will be only a fraction of the magnitude of the zero-shift itself.

Appendix A is a compilation of the computer printouts of the data points for static and transient apparent strain for each gage and each cycle. The plots shown represent hand-drawn curves, which were faired through the data points. In general, the curves represent the heating up portions of each of the 3 cycles. In some instances more than 3 curves appear on a plot; these additional curves represent the corresponding cool-down portions of the cycles. Data points through which no curves are drawn, in general, represent data points during cool-down, through which curves were not drawn to avoid clutter. The remaining data points are extraneous

points. The voluminous amount of data in this appendix is included in this report for future reference.

Table 4 summarizes the gage-to-gage and cycle-to-cycle variations in apparent strain at 1311 K (1900 F). These values were computed from the raw data which are depicted, graphically, in Appendix A. (similar comparisons were not made at intermediate temperatures, because of the extensive amount of interpolation required to account for the differences in intermediate temperatures at which strain data were recorded for the static and transient apparent strain runs.)

An inspection of Table 4 indicates that (a) cycle-to-cycle variations, in terms of maximum DFM, range from 0.3 percent to 2.9 percent, (b) the gage-to-gage variations, in terms of maximum DFM, range from 7.1 percent to 9.8 percent, with the largest value for the static condition, and (c) as mentioned earlier, there is a progressive but small increase in apparent strain with increasing heating rate.

7.2.2.5 Drift Characteristics

Figure 19 is a drift plot at 1311 K (1900 F) over a 2 hour and 45 minute span in time for each of the operating gages on Specimen IN-2. The solid line represents the average of the data points. The gage-to-gage variation is considered normal. It is noted that the drift rate is the highest over the first 20 minutes, and that it tends to be uniform after 30 minutes. The average dirft rate over the entire time span is -194 $\mu\epsilon$/hr. Over a 2.5-hour span, the average drift rates at 1311 (1900 F) for Specimens IN-2, H-29, and H-32 are:

Specimen	Average Drift Rate, $\mu\epsilon$/hr.
IN-2	-192
H-29	-88
H-32	-170

Note: Data for Specimens H-29 and H-32 were taken from Figures 23 and 24 of Reference 2.

TABLE 4. SUMMARY OF APPARENT STRAINS AT 1311 K (1900 F)

Gage	Cycle	Static	0.55 K/sec (1 F/sec)	1.67 K/sec (3 F/sec)	2.78 K/sec (5 F/sec)
1	1	19772	23780	25880	27040
	2	19952	23816	26136	27456
	3	20196	24080	26260	27668
	Mean =	19973	23892	26092	27388
	Max. % DFM* =	1.1	0.8	0.8	1.3
2	1	17514	21154	23132	24292
	2	17866	21381	23360	24824
	3	18232	21773	23572	25656
	Mean =	17871	21436	23355	24924
	Max. % DFM =	2.0	1.5	1.0	2.9
3	1	17378	21456	23503	24577
	2	17472	21804	23619	24822
	3	17507	21648	23702	24935
	Mean =	17452	21636	23608	24778
	Max. % DFM =	0.3	0.8	0.4	0.8
5	1	21016	24752	26740	27900
	2	21052	24784	26994	28652
	3	21244	24992	27096	28764
	Mean =	21104	24843	26943	28439
	Max. % DFM =	0.7	0.6	0.8	1.9
7	1	---	---	25667	---
	2	19630	23649	25833	---
	3	19751	23825	---	---
	Mean =	19690	23749	25750	---
	Max. % DFM =	0.3	0.4	0.3	---
Gage to Gage Mean =		19218	23111	25150	26382
Max. Gage % DFM =		9.8	7.5	7.1	7.8

*Deviation from mean.

It should be pointed out that the Specimens H-29 and H-32 were prestabilized for 4 hours at 1325 K (1925 F), whereas Specimen IN-2 was prestabilized at the same temperature but for only 2 hours--on the basis of the more optimum prestabilization curves presented in Figure 5. It is evident that, while less gage life was consumed during prestabilization for the shorter time period, any resulting increase in remaining gage life was obtained at the expense of a somewhat higher drift rate. Nevertheless, these somewhat higher drift rates are no larger than those exhibited by commercial high-temperature gages at temperatures as low as 922 K (1200 F). In any event, since these gages were developed to have a minimum useful life of 1/2-hour--in accordance with NASA target requirements--the drift correction would be small for tests of this short duration; and, of course, the error in strain reading, due to drift, after correcting for drift with the aid of the drift calibration curve such as shown in Figure 19, would be even smaller.

7.3 Verification of Repeatability of Apparent Strain During Cool-Down and Heat-Up

Figures 6 through 9 are apparent strain plots during heat-up and cool-down for the gages on Haynes 25, Specimens PS-2-1, and PS-3. Figure 6 represents the average apparent strain to 1366 K (2000 F) for the 3 gages on Specimen PS-2-1. It is noted that, in spite of a zero-shift of -1000 $\mu\epsilon$ during second cycle cool-down, the second cycle heat up closely follows the previous cool-down, except at the lower temperatures where the maximum deviation is approximately 400 $\mu\epsilon$.

Figures 7, 8, and 9 are similar plots to 1311 K (1900 F) for the individual Gages 1, 2, and 3. The same type of behavior is noted. It is believed that this behavior provides further verification of the findings reported in References 1 and 2; namely, that the apparent strain curves for the BCL gages characteristically converge at the maximum evaluation temperature, and that the heat-up portion of the apparent strain cycle retraces, within very close limits, the previous cool-down cycle, because of the convergence characteristic. This characteristic provides a means

of significantly improving the accuracy of strain measurement in those applications where it is possible to thermally precycle the gages, after installation, to obtain the apparent strain curve during cool-down. It is believed that this curve can then be used with confidence as an apparent strain calibration curve to correct test data obtained during heat-up. Further, if the test can be conducted within the temperature range of maximum retraceability, even greater improvement in measurement accuracy is possible. Referring to Figure 6, it is noted that between 644 K (700 F) and 1966 K (2000 F), retraceability is excellent. For example, many of the transient heating and cooling tests that are performed for liquid metal reactor piping systems and other high temperature systems, are performed within these temperature limits. Higher strain measurement accuracy in these applications should, therefore, be possible.

7.4 Sputter-Clad BCL-3 Gages

During gage fabrication, it was noted that the platinum cladding remained intact, except at the 180 degree bends around the .33 mm (0.0132 in.) diameter pins of the strain gage winding fixture. Here a small amount of spalling was noted. During Rokiding of the 2 platinum-clad BCL-3 gages and 2 standard BCL-3 gages, to Specimen H-33, there was no observable damage to any of the gages from the Rokiding after the prestabilization. It was found during the apparent strain evaluation that there was no significant difference in the general shapes of the curves, and no difference in the zero-shifts between the two types of gages. However, the apparent strain was somewhat higher than that of the standard BCL-3 gages (23,000 $\mu\varepsilon$ versus 17,500), indicating that the cladding thickness and prestabilization combination was not optimum. Nevertheless, it was demonstrated by this limited effort that it is feasible to fabricate sputter-clad BCL-3 gages, without undue spalling, or other effects which might make fabrication impractical.

CONCLUSIONS

The prestabilization drift vs temperature curves (Figure 5) provide a rational basis for determining how long BCL gages should be prestabilized at any given temperature within the range of 1200 K (1700 F) to 1366 K (2000 F). Utilization of these curves should increase remaining gage life beyond that previously obtainable for gages subjected to the longer prestabilization times (>4hr). Also, utilization of these curves will substantially reduce the magnitude of the correction for apparent strain. At 1311 K (1900 F), the static apparent strain is reduced from approximately 53,000 to 57,000 to approximately 19,200 $\mu\epsilon$. This corresponds to a reduction in apparent strain of at least 64 percent. Similar reductions in transient apparent strain are presumed. However, the magnitude of the reduction is not known, since transient apparent strain characteristics were not determined in the previous program.

Since the gage factor, drift, and zero-shift program differ little from those in the previous program, it is concluded that the major benefits--namely the 64 percent reduction in apparent strain and longer remaining gage life resulting from shorter prestabilization times--clearly outweigh the small compromises, if any, in drift stability or other gage characteristics.

Additional study of the BCL gage retraceability characteristics reported in Reference 2 has further verified that this characteristic provides a viable means of enhancing measurement accuracy--particularly in the temperature range of 644 K (700 F) to 1300 K (2000 F).

The limited study on the feasibility of fabricating BCL platinum-clad gages has demonstrated that it is possible to wind gages without excessive spalling of the cladding at the 180° bends around the 0.33 mm (013 in.) diameter pins of the strain gage winding fixture. However, because the limited scope of the study, it was not possible to assess the significance of minor spalling or the degree of protection against oxidation offerred by the cladding. (A prior study reported in Reference 2 vividly

demonstrated temperature compensation effectiveness of the platinum cladding to 1089 K (1500 F); hence, no further study relative to temperature compensation effectiveness of the cladding, was undertaken in this program.)

Finally, it is concluded that, on the basis of the results from this program, and the supporting information obtained under Contract NAS1-12099 and reported in Reference 2, the BCL strain gage system herein described, should perform satisfactorily up to temperatures approaching 1367 K (2000 F), under static conditions and transient heating rates of at least 2.78 K/sec (5 F/sec). Since the cycle-to-cycle repeatability under transient heating was even better than under static conditions, and since prior studies described in Reference 2 indicated that the BCL gage could withstand thermal shocks (at least 25) to 39 K/sec (70 F/sec) and severe mechanical impact in a Hopkinson apparatus, it is believed that the BCL gage can be used for measurement of strain at transient heating rates considerably faster than 2.78 K/sec (5 F/sec).

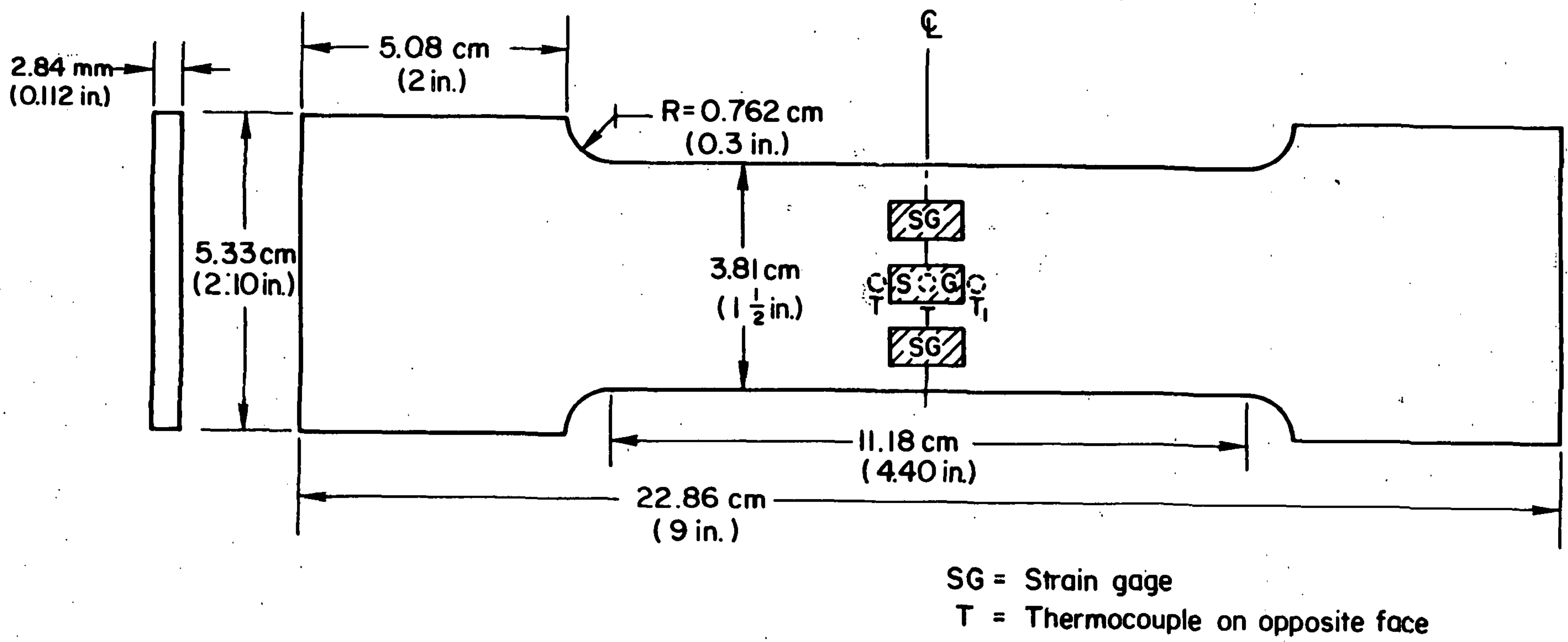


FIGURE 1. PRESTABILIZATION STUDY SPECIMEN

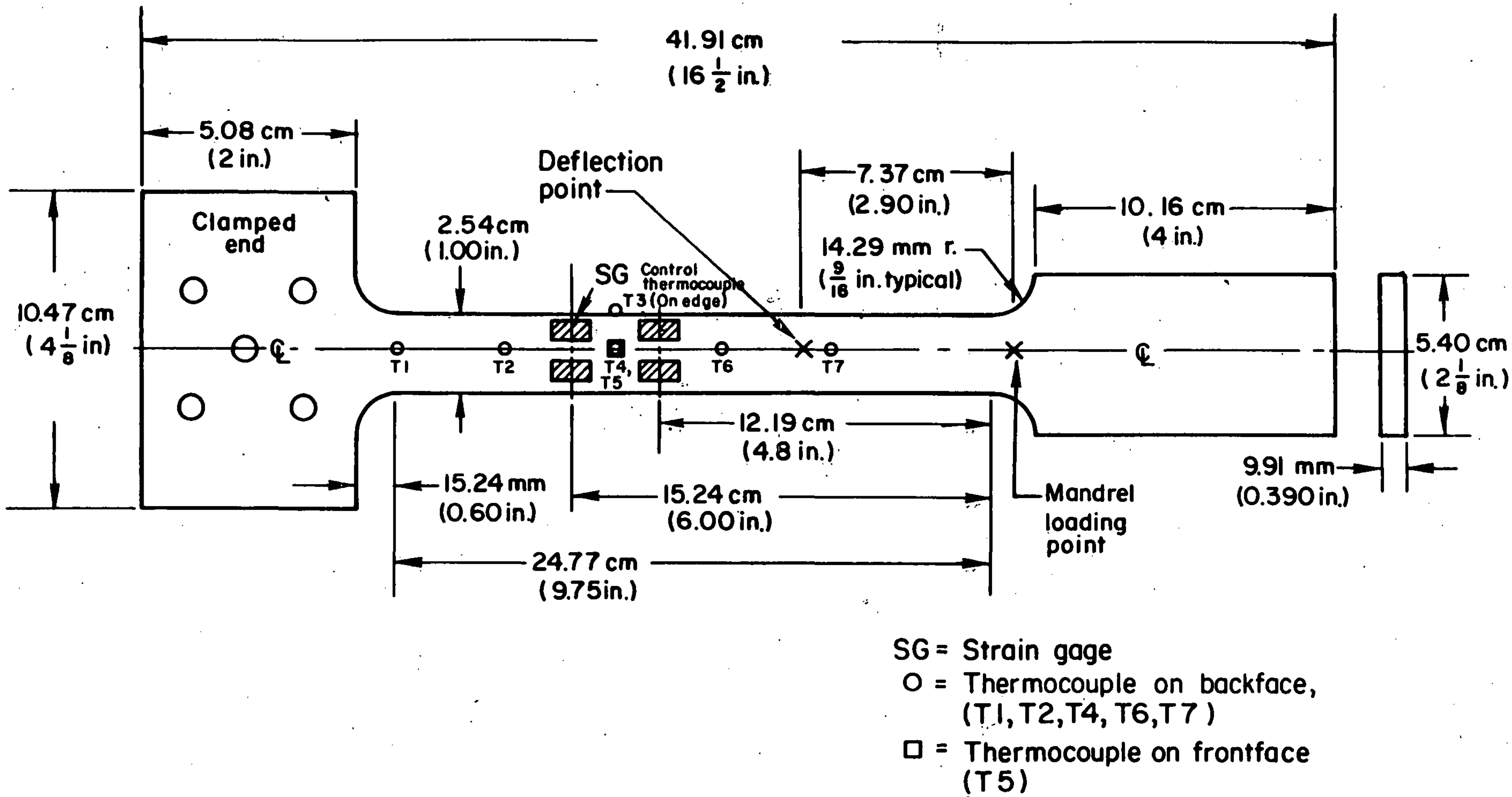


FIGURE 2. GAGE EVALUATION SPECIMEN

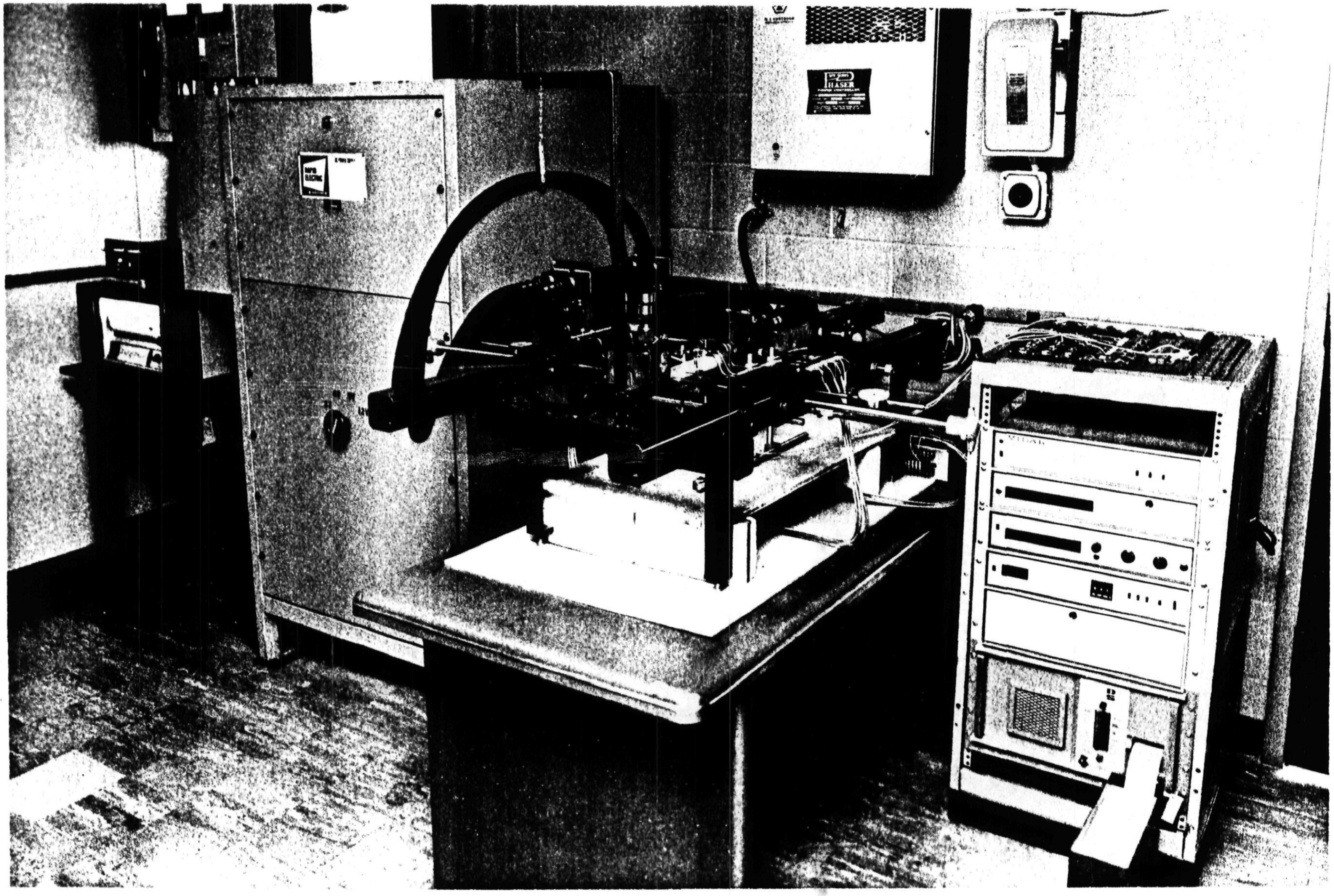


FIGURE 3. OVERALL VIEW OF HIGH-TEMPERATURE GAGE EVALUATION FACILITY

9653

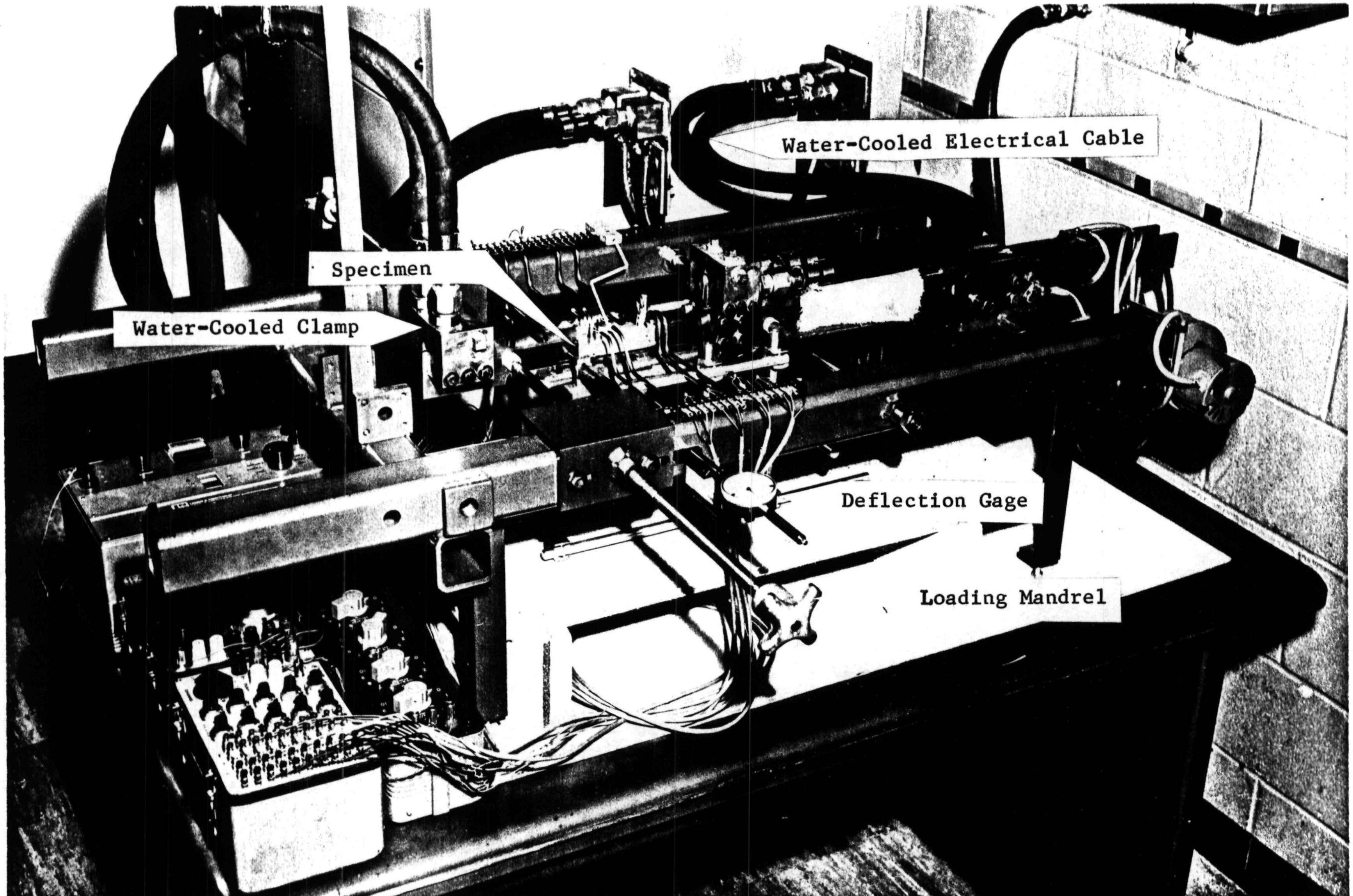


FIGURE 4. CLOSE-UP VIEW OF HIGH-TEMPERATURE GAGE EVALUATION FACILITY

7053

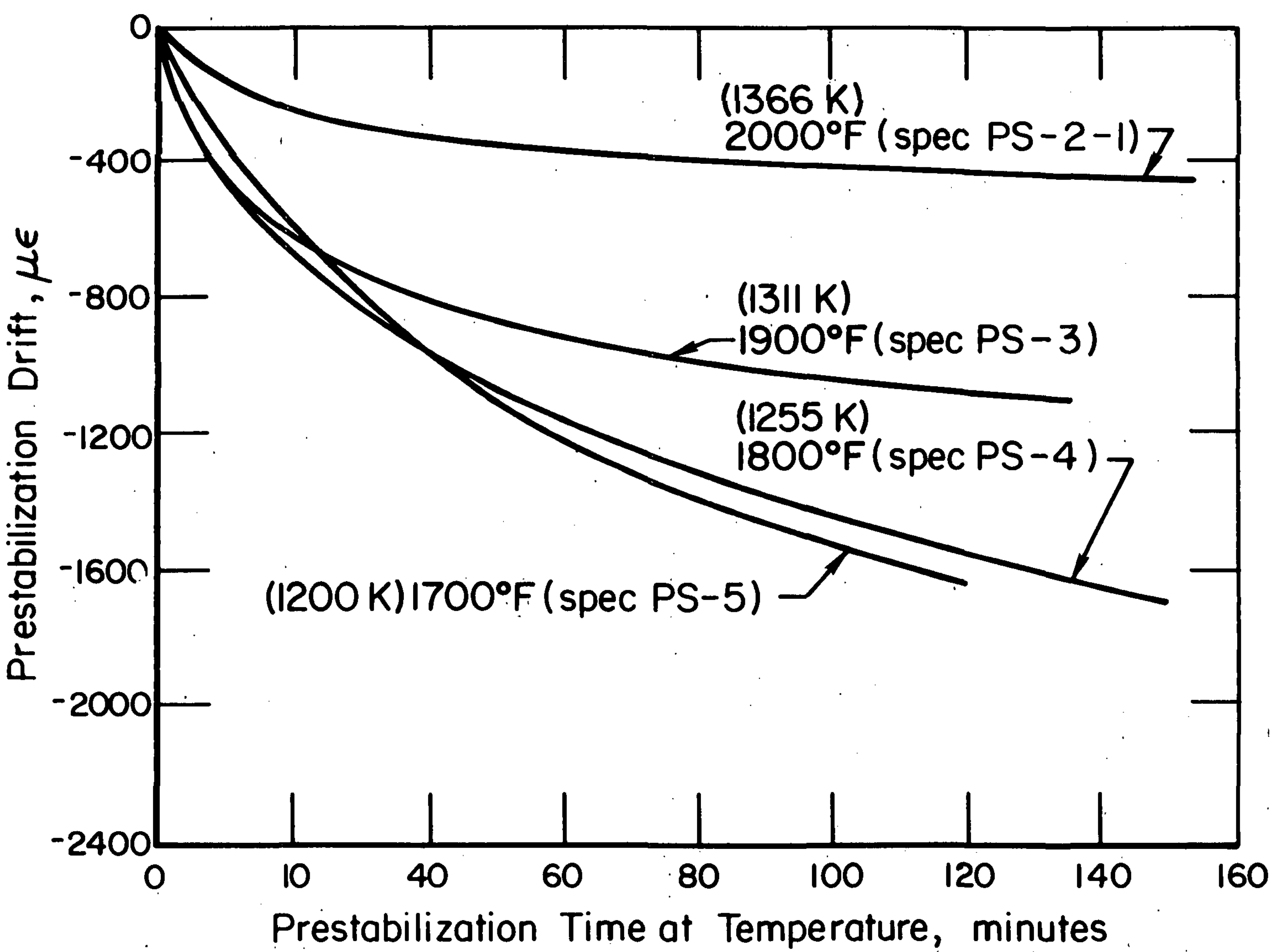


FIGURE 5. PRESTABILIZATION DRIFT VERSUS TIME

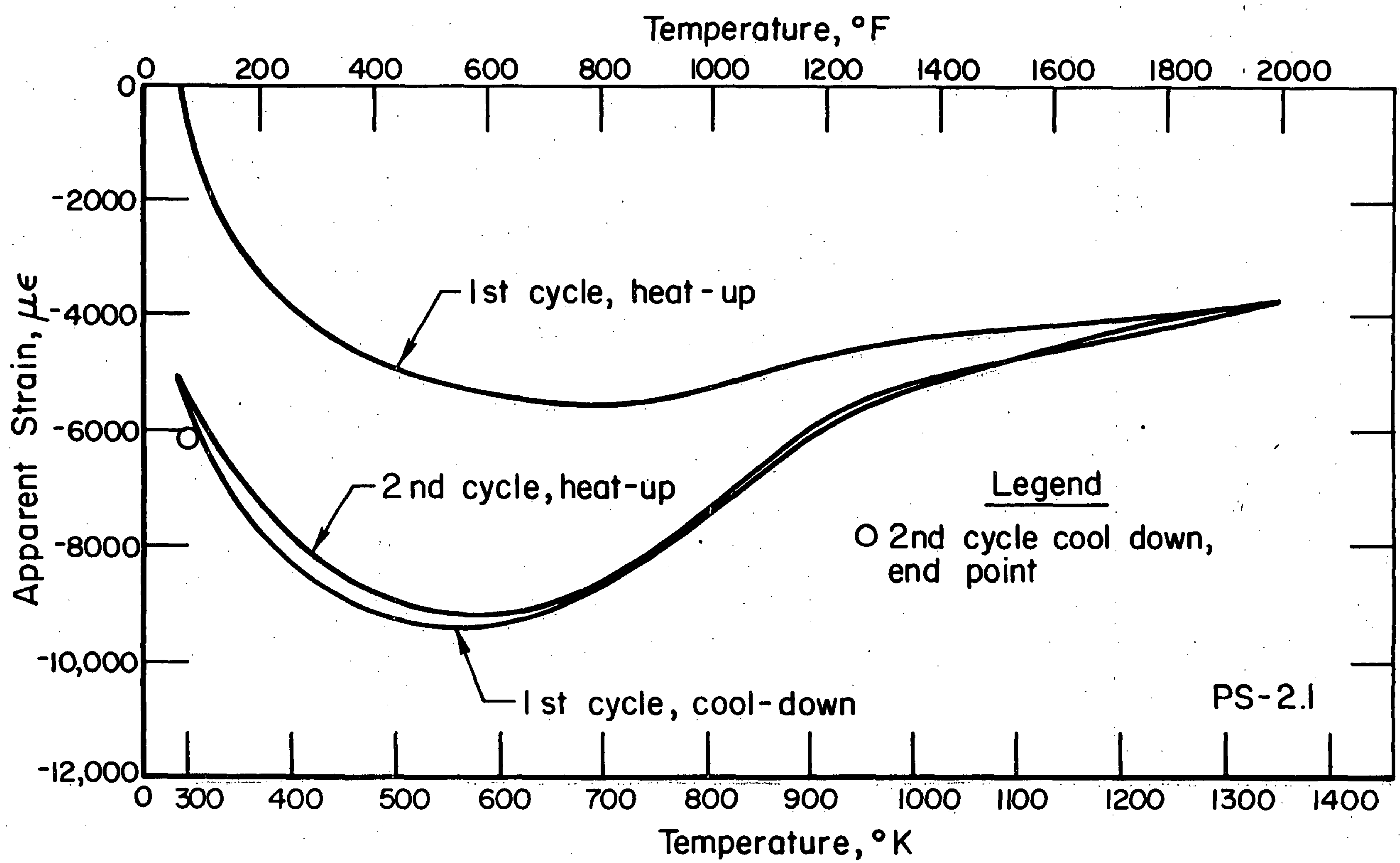


FIGURE 6. APPARENT STRAIN VERSUS TEMPERATURE TO 1366 K (2000 F), AV. OF 3 GAGES

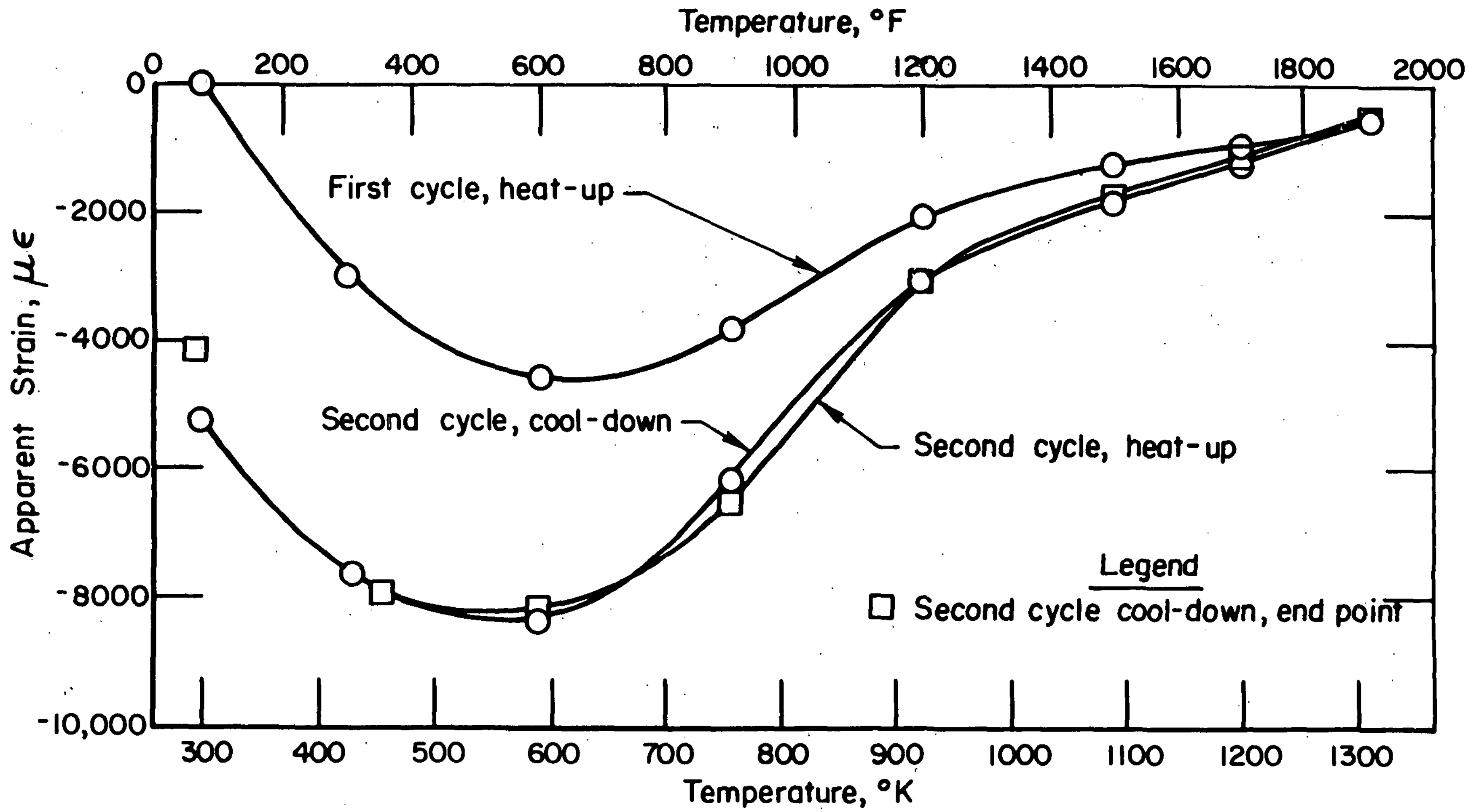


FIGURE 7. APPARENT STRAIN TO 1311 K (1900 F), GAGE 1, SPECIMEN PS-3

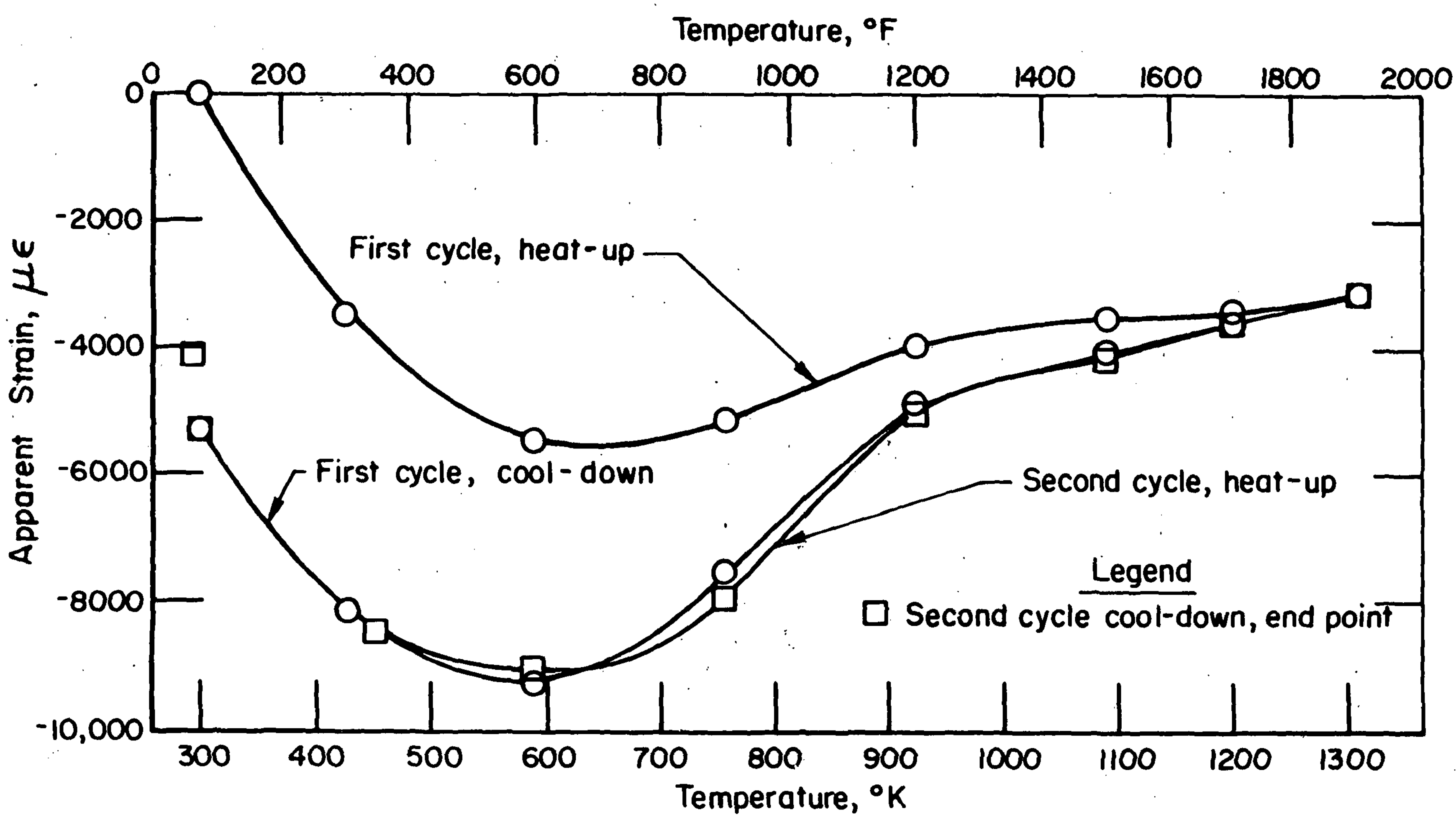


FIGURE 8. APPARENT STRAIN TO 1311 K (1900 F), GAGE 2, SPECIMEN PS-3

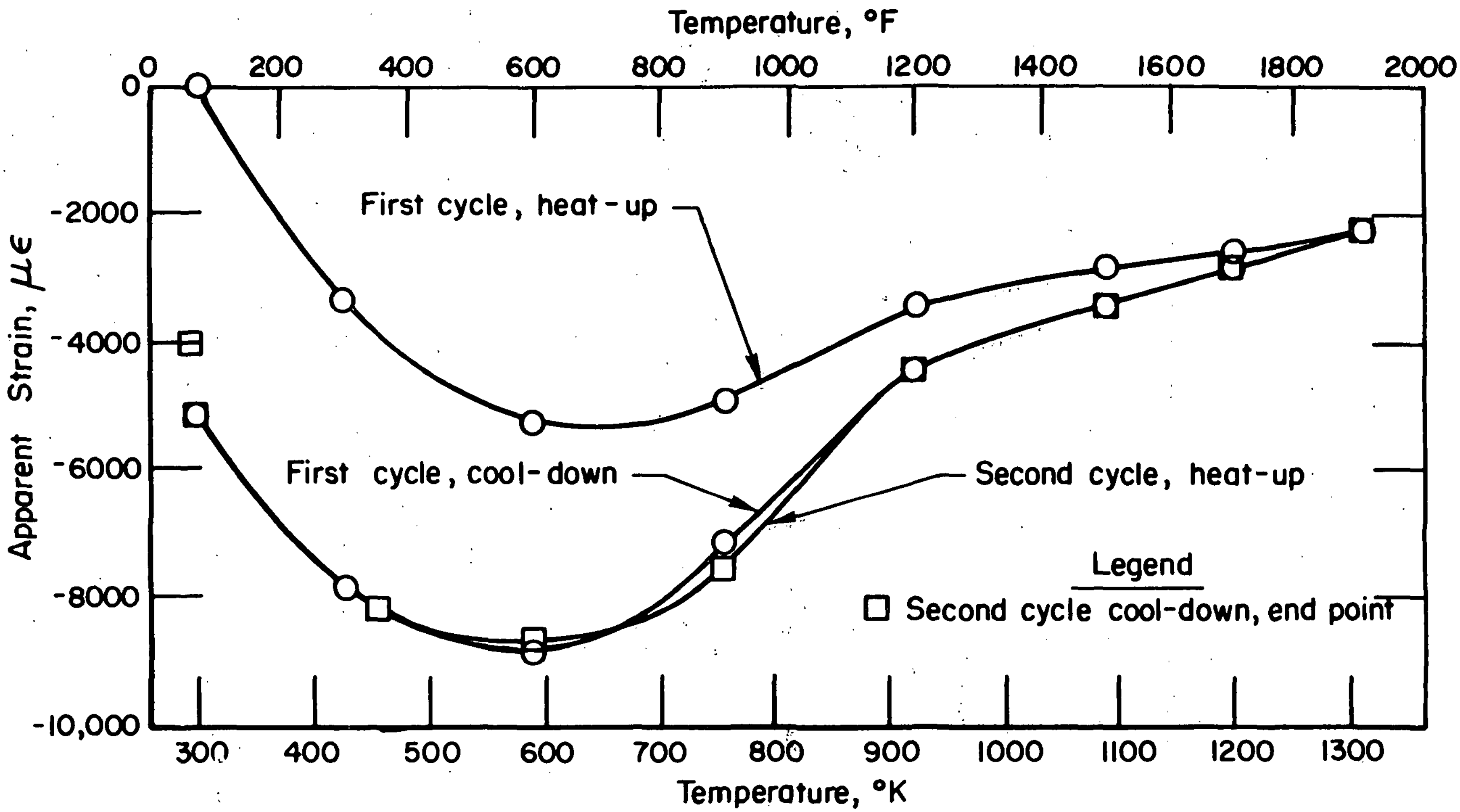


FIGURE 9. APPARENT STRAIN TO 1311 K (1900 F), GAGE 3, SPECIMEN PS-3

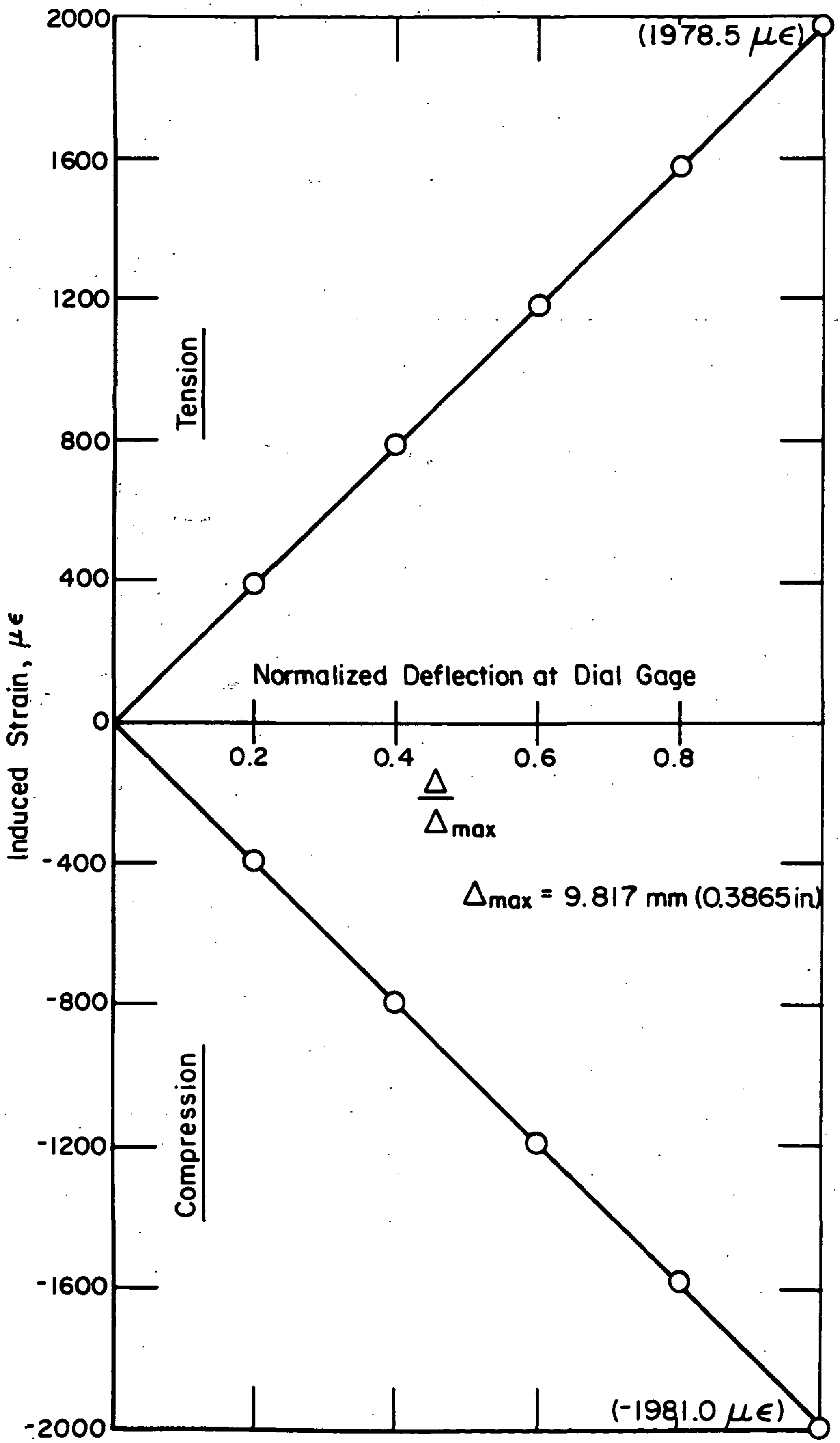


FIGURE 10. LOADING SYSTEM DEFLECTION VERSUS STRAIN CALIBRATION

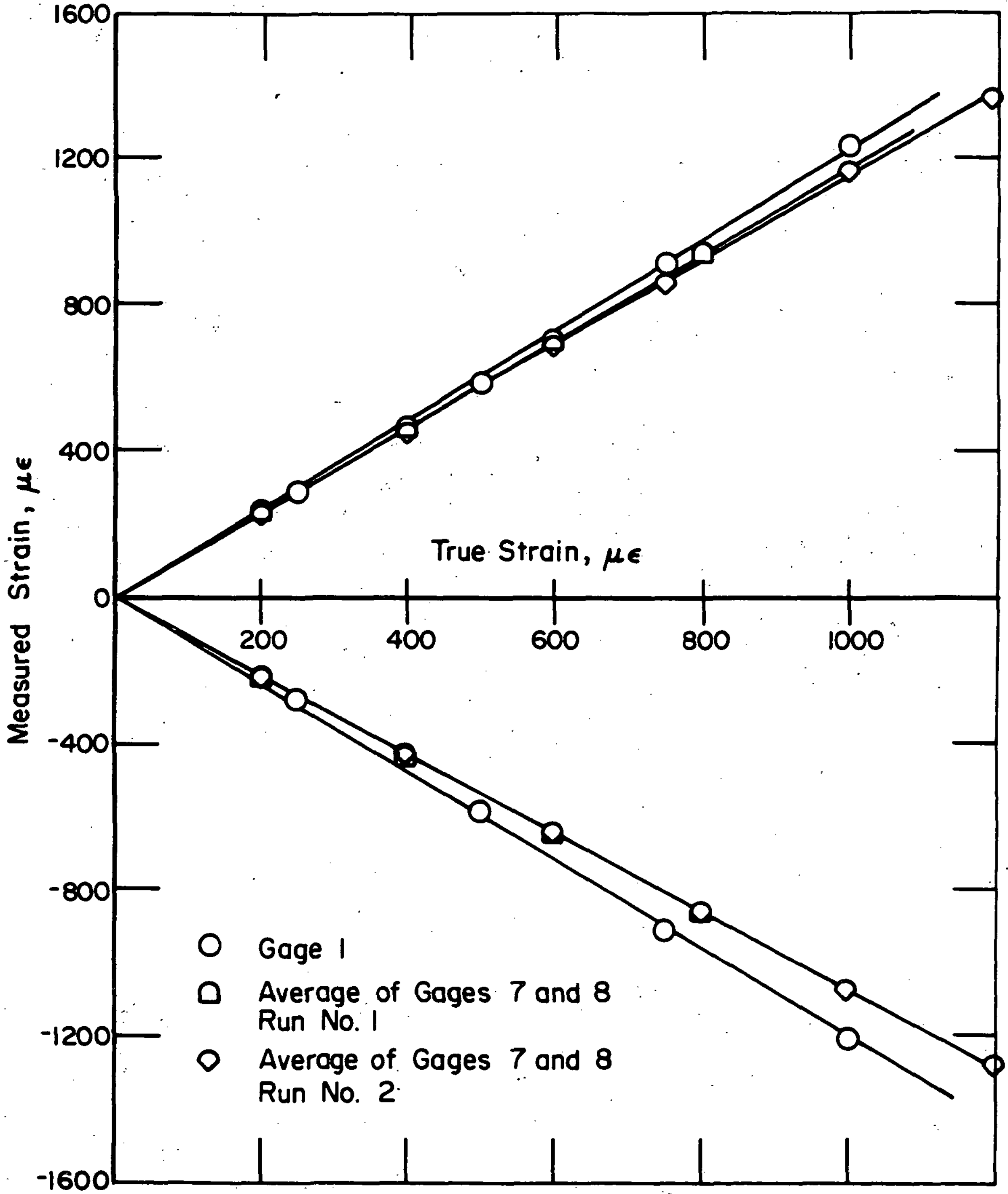


FIGURE 11. STRAIN RESPONSE, ROOM TEMPERATURE

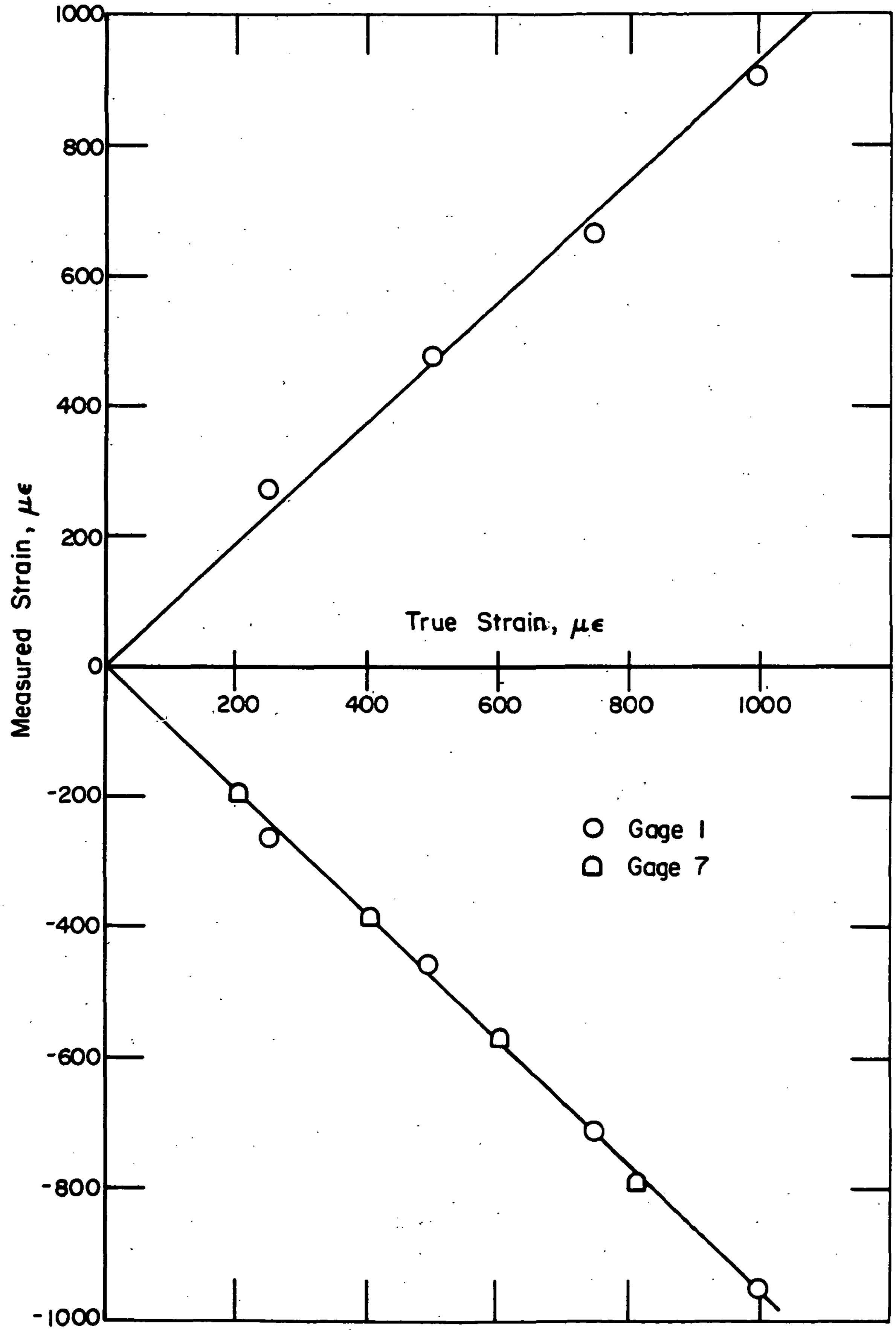


FIGURE 12. STRAIN RESPONSE, 922 K (1200 F)

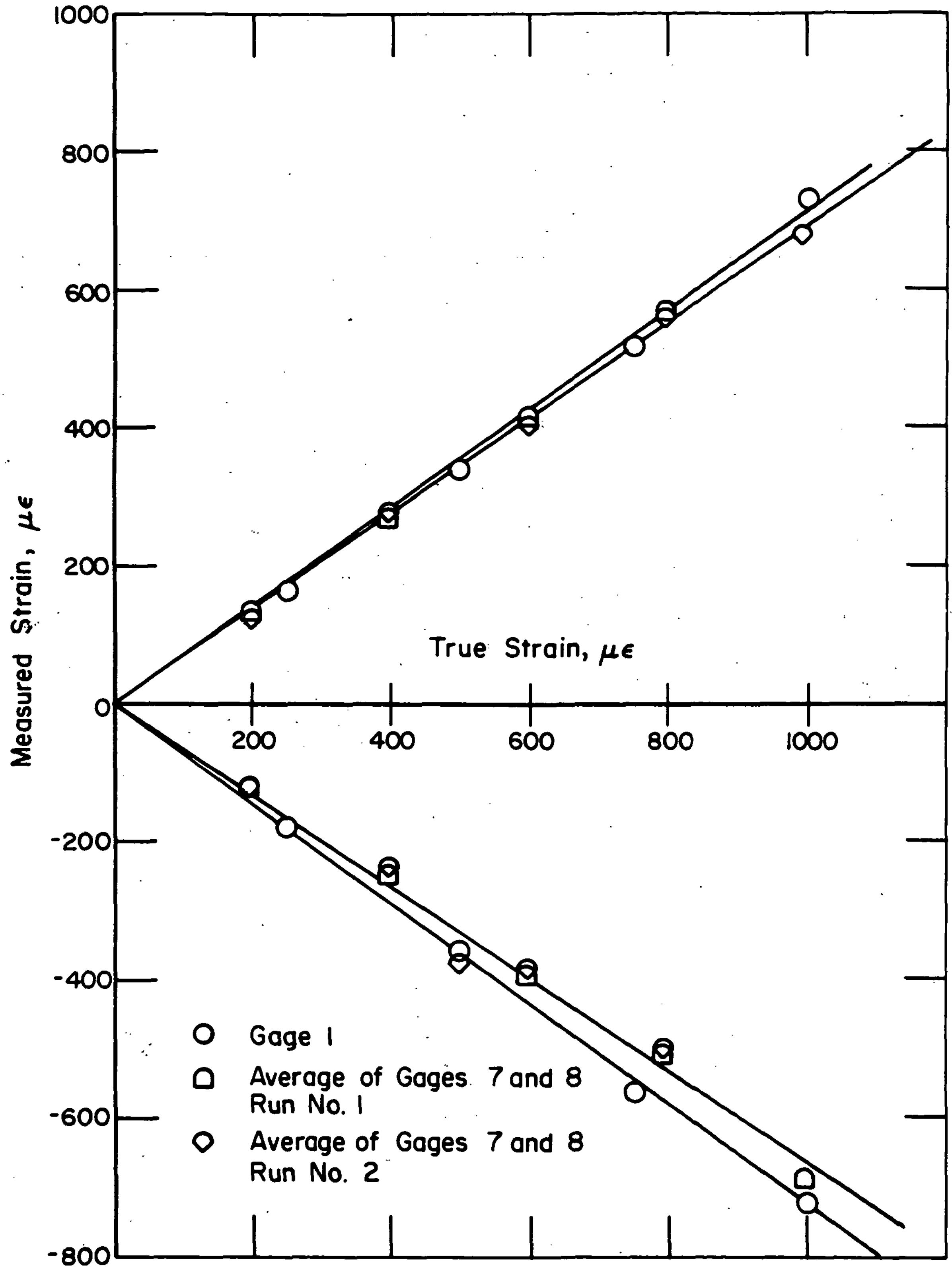


FIGURE 13. STRAIN RESPONSE, 1311 K (1900 F)

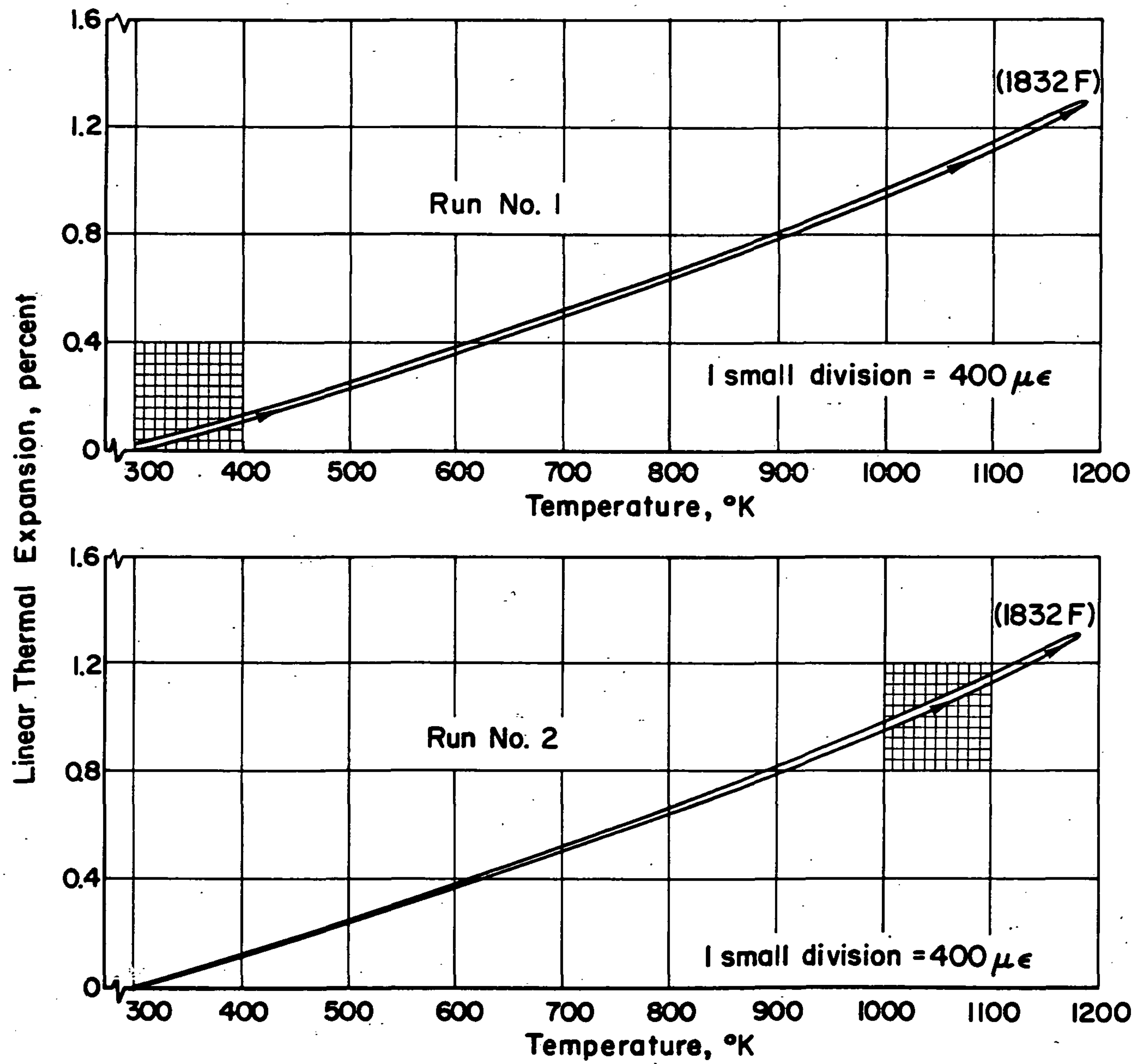


FIGURE 14. DIMENSIONAL CHANGES, IN 100 SPECIMEN

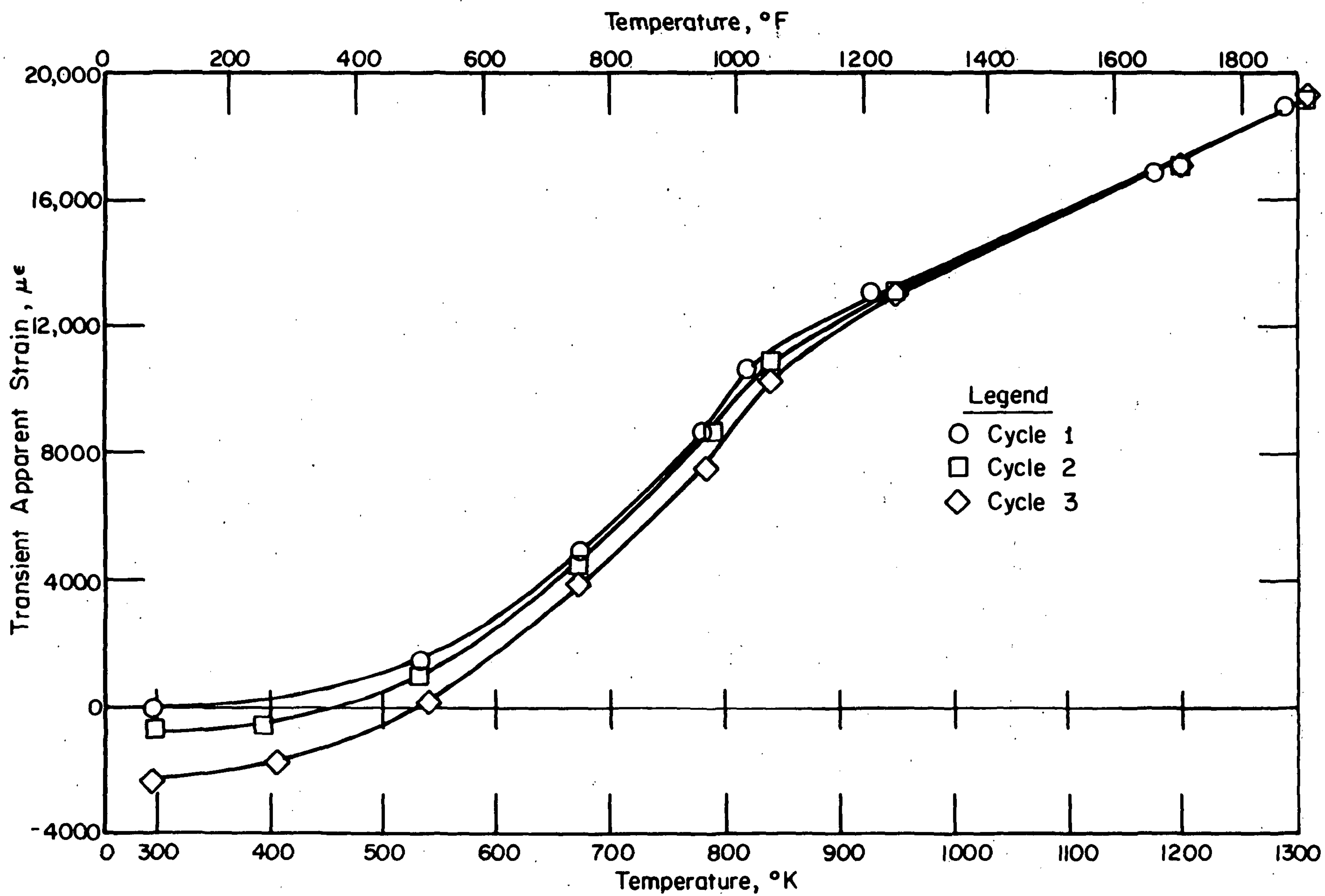


FIGURE 15. STATIC APPARENT STRAIN TO 1311 K (1900 F)

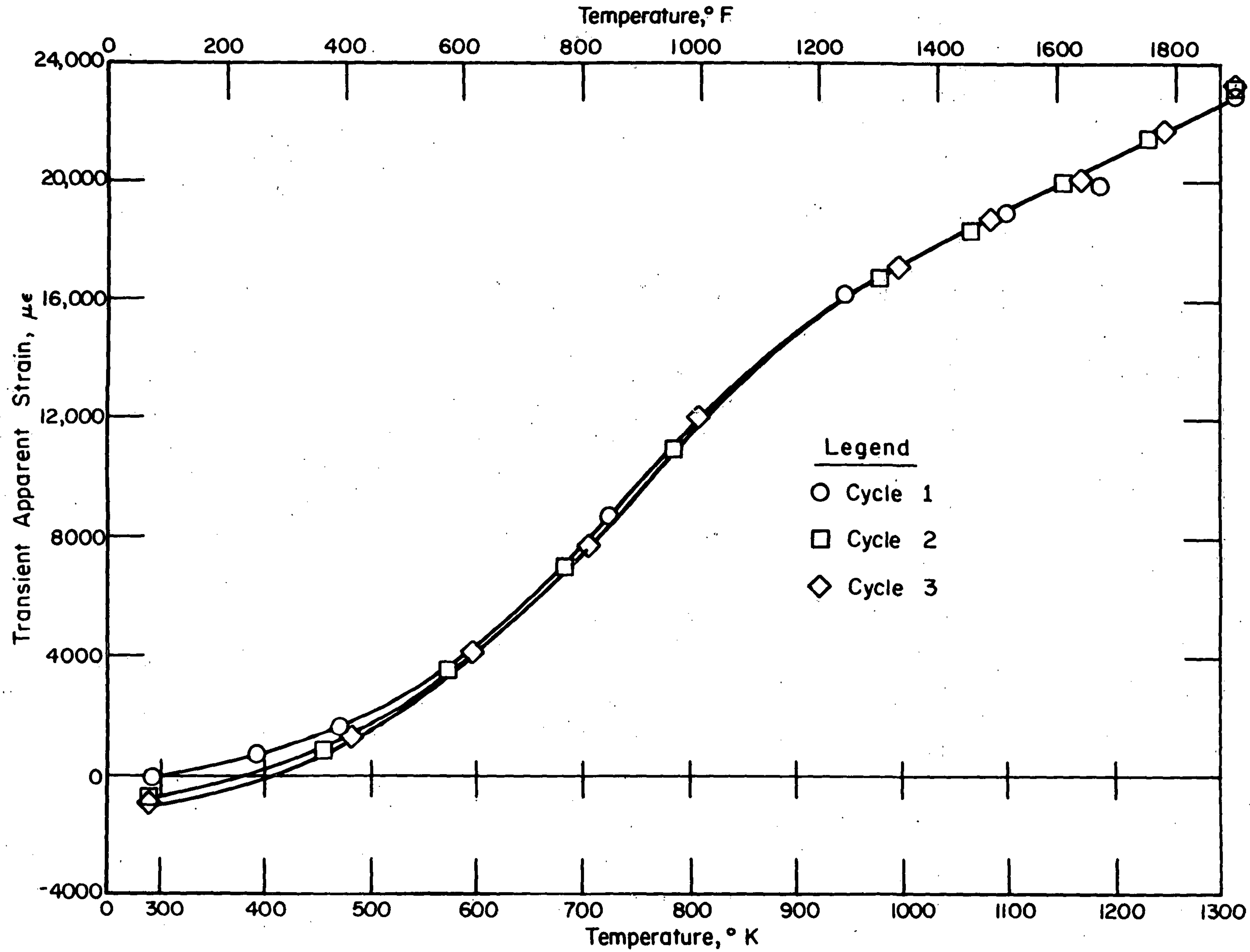


FIGURE 16. TRANSIENT APPARENT STRAIN TO 1311 K (1900 F), 0.55 K/SEC (1 F/SEC)

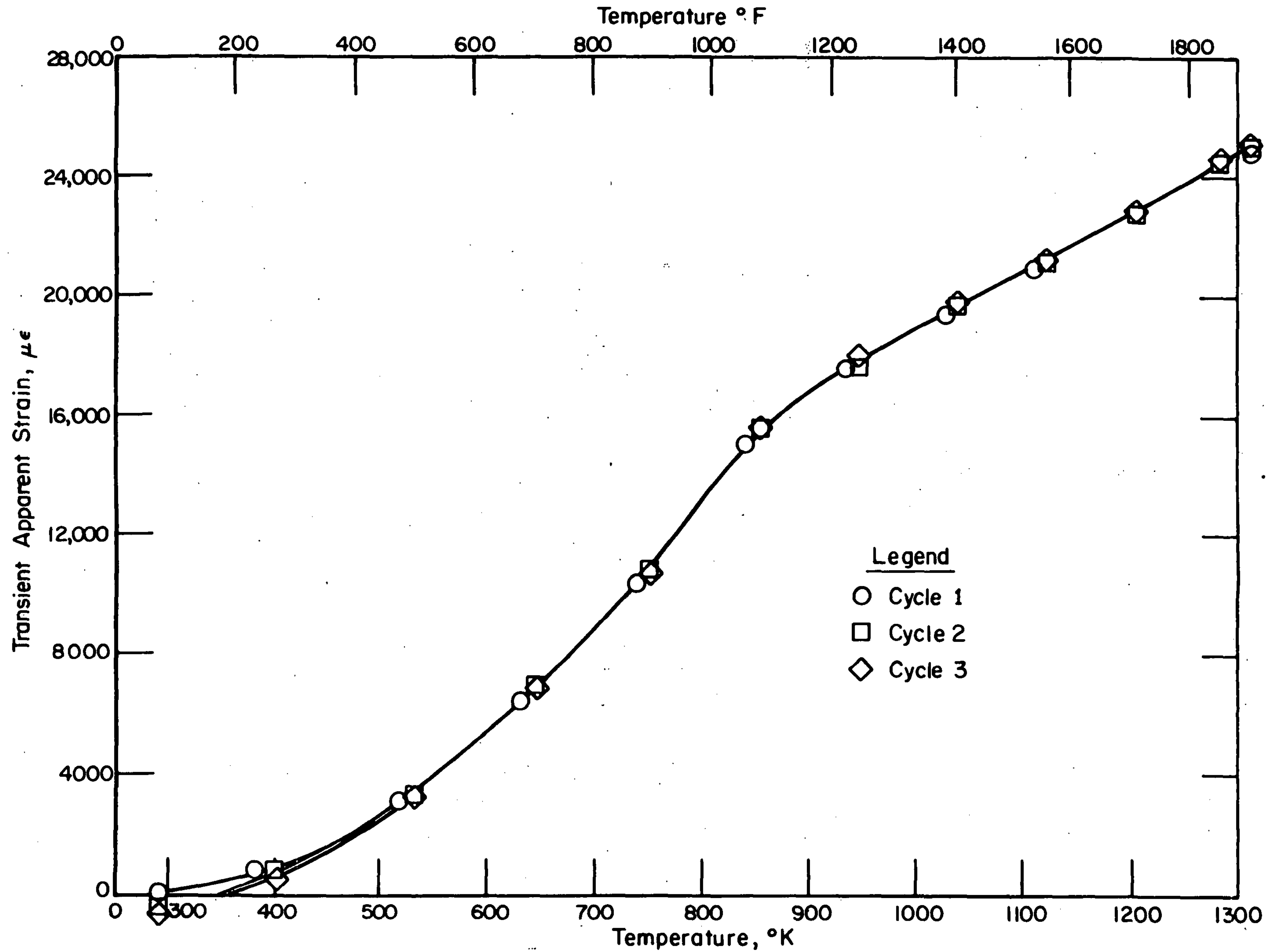


FIGURE 17. TRANSIENT APPARENT STRAIN TO 1311 K (1900 K), 1.67 K/SEC (3 F/SEC)

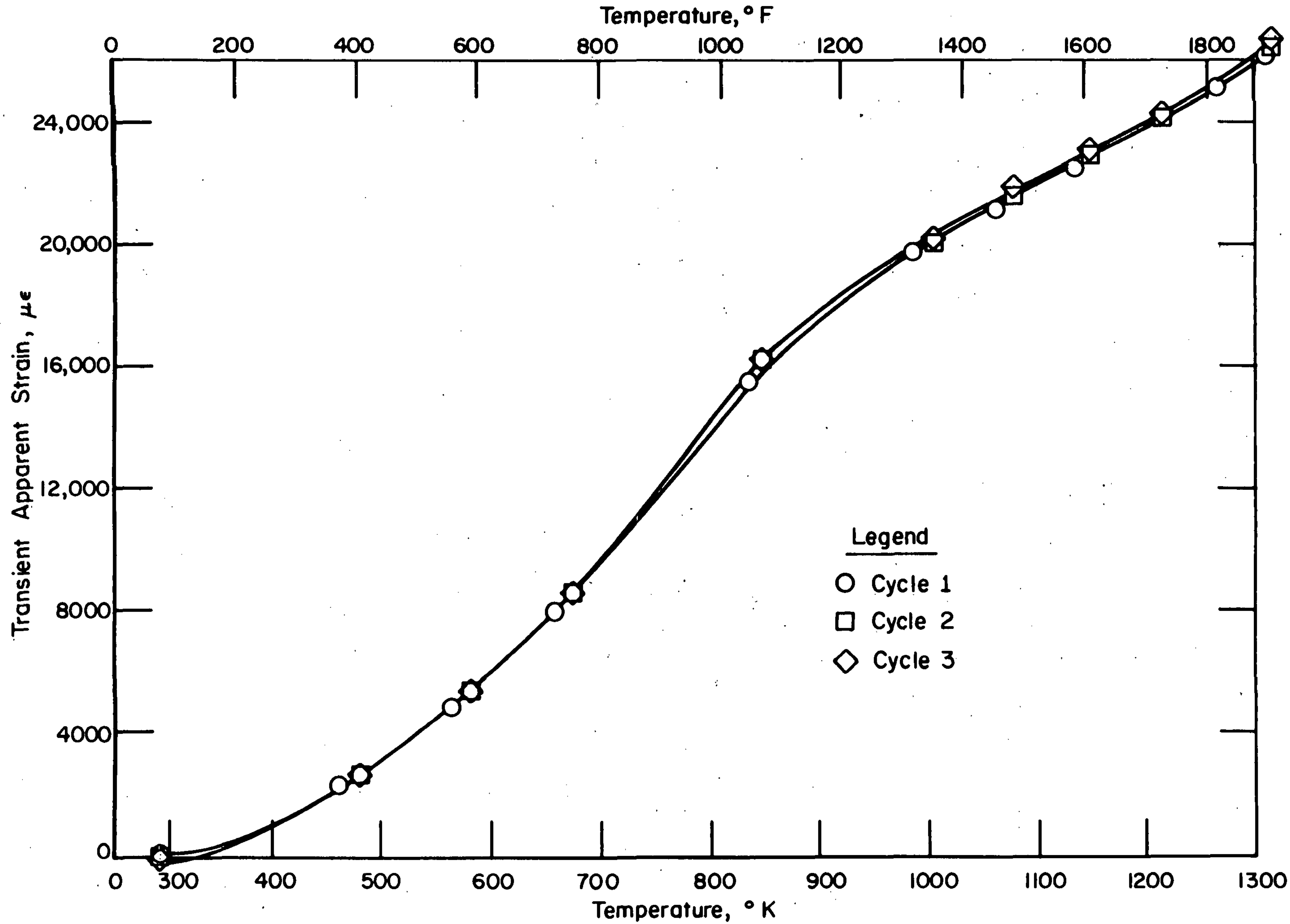


FIGURE 18. TRANSIENT APPARENT STRAIN TO 1311 K (1900 K), 2.78 K/SEC (5 F/SEC)

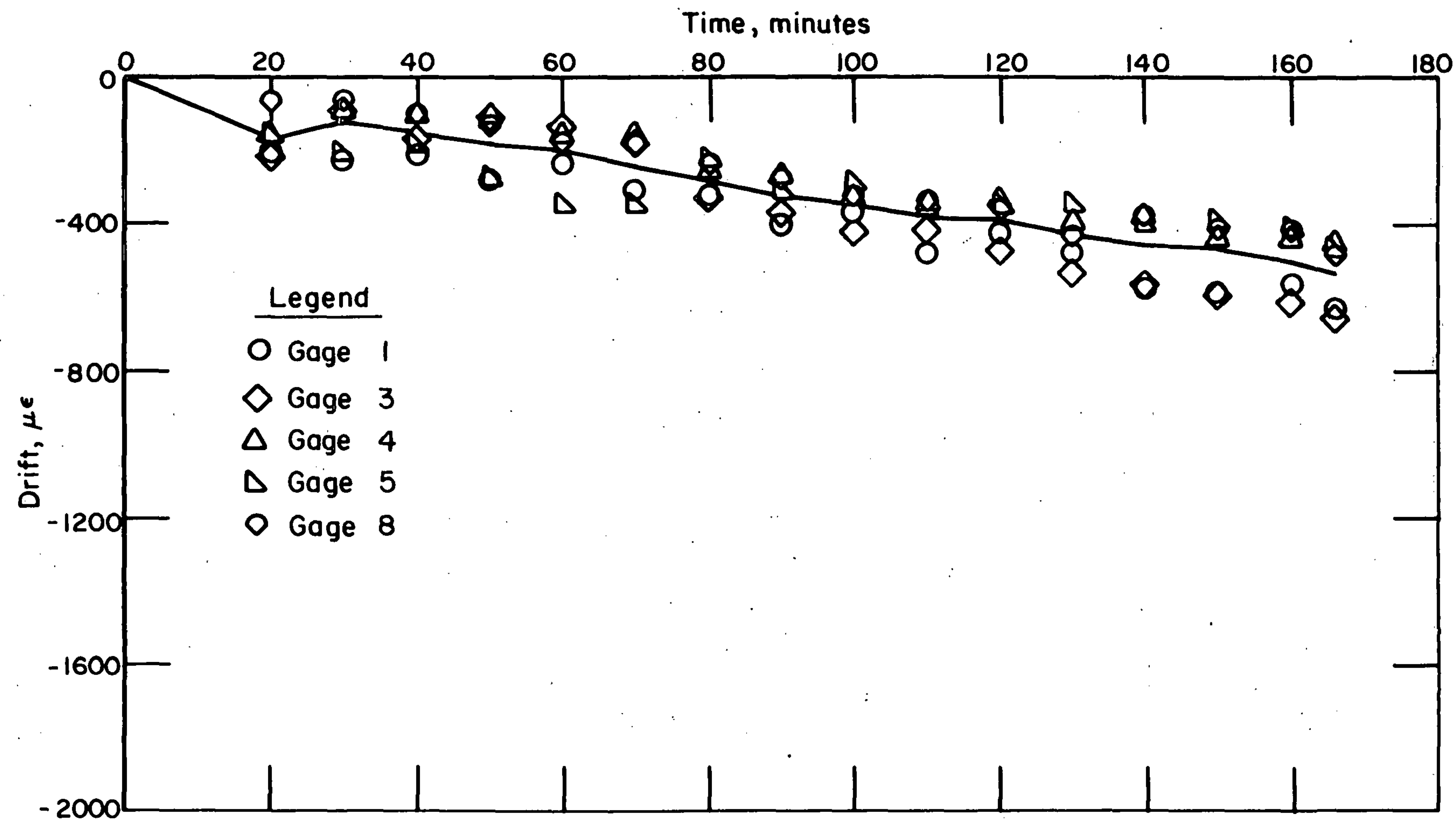


FIGURE 19. DRIFT AT 1311 K (1900 F)

LIST OF REFERENCES

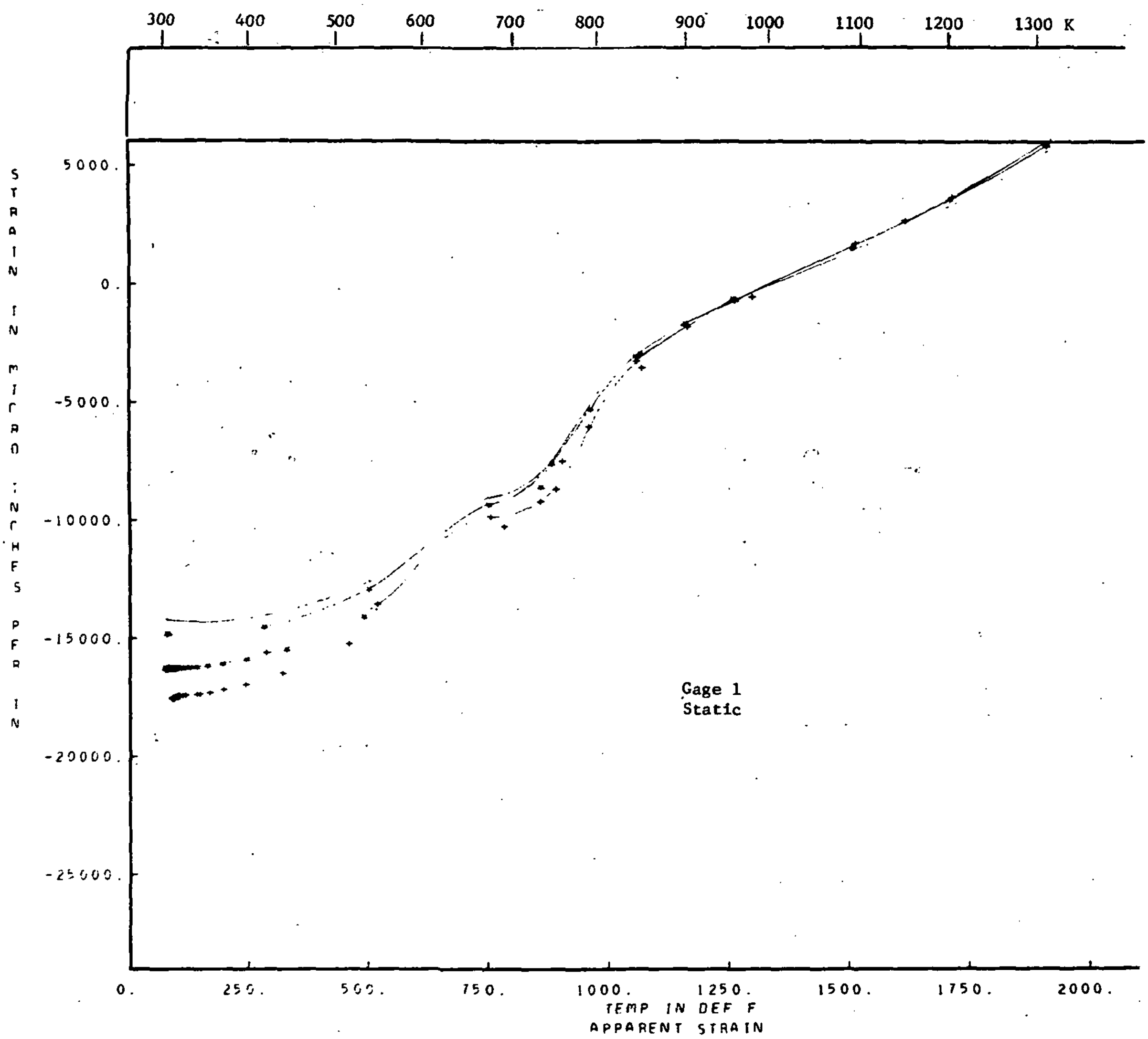
1. Lemcoe, M. M., "Development of High-Temperature Strain Gages", NASA CR-112241, 1973.

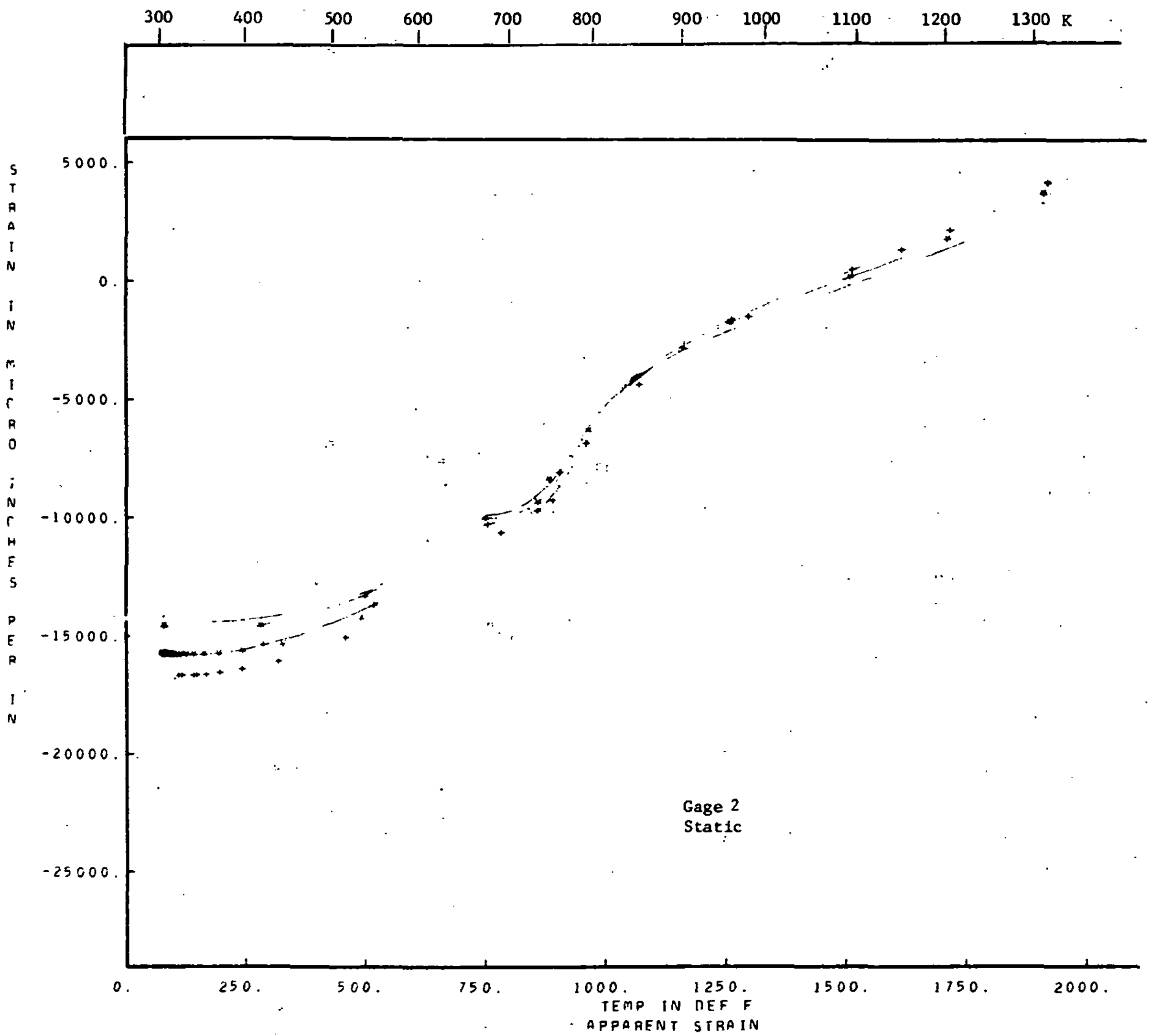
2. Lemcoe M. M., "Development of Strain Gages for Use to 1311 K (1900 F)", NASA CR-132485, 1974.

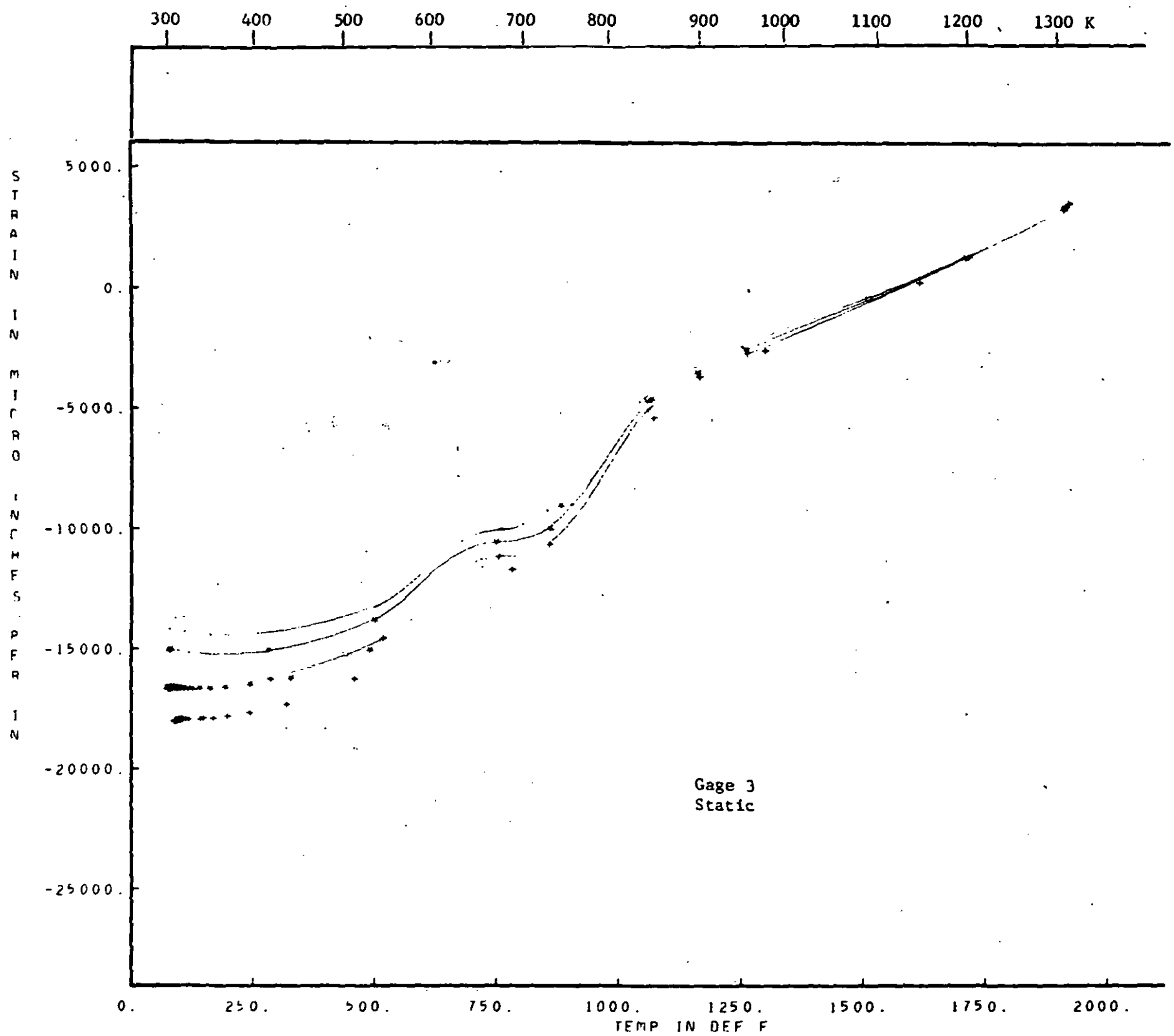
3. The International Nickel Company Incorporated, "High-Temperature -- High-Strength Nickel Base Alloys", 1964.

APPENDIX A

APPARENT STRAIN, RAW DATA


300
400
500
600
700
800
900
1000
1100
1200
1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
Gage 1
Static
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN


300 400 500 600 700 800 900 1000 1100 1200 1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0. 250. 500. 750. 1000. 1250. 1500. 1750. 2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 2
Static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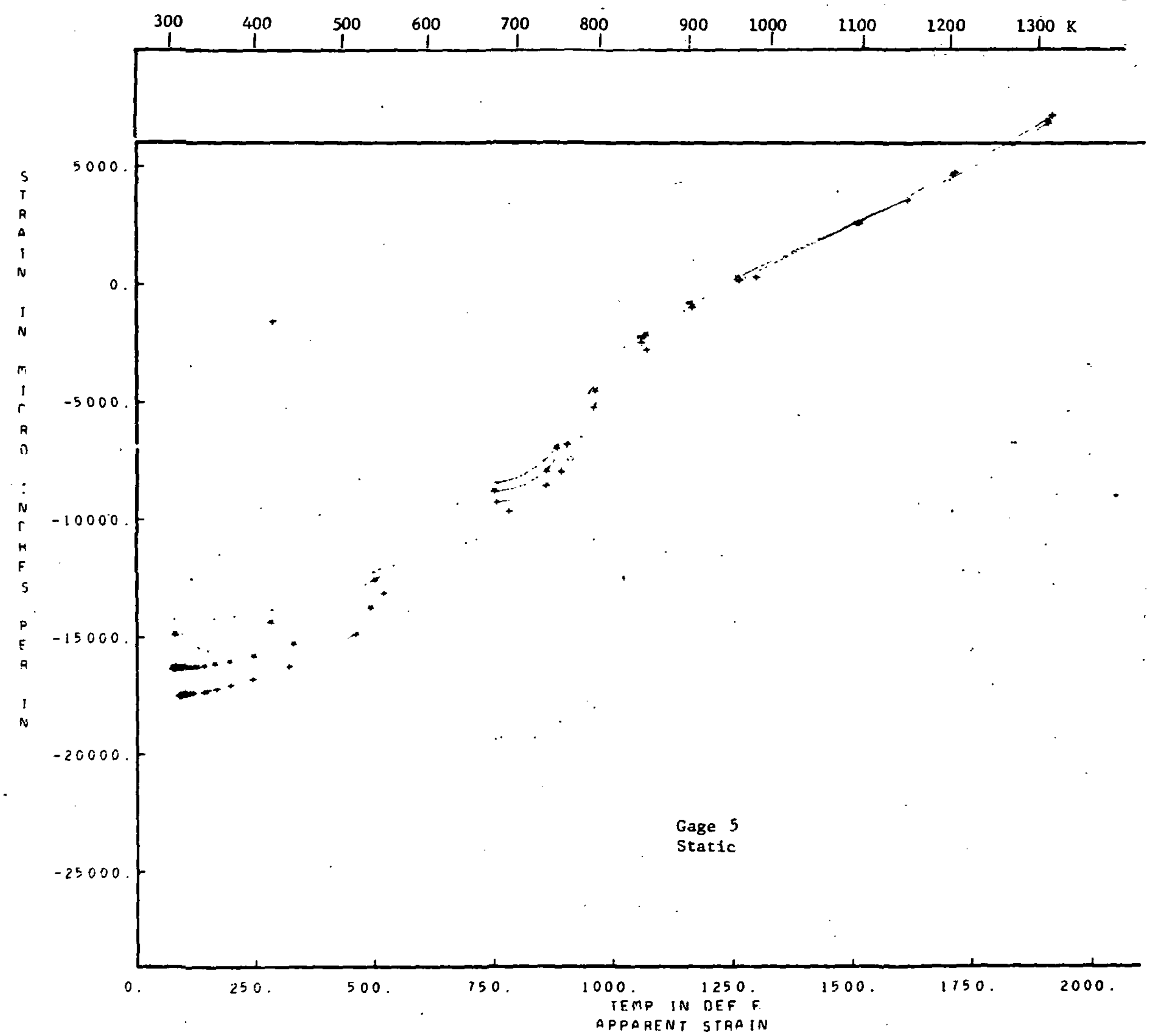
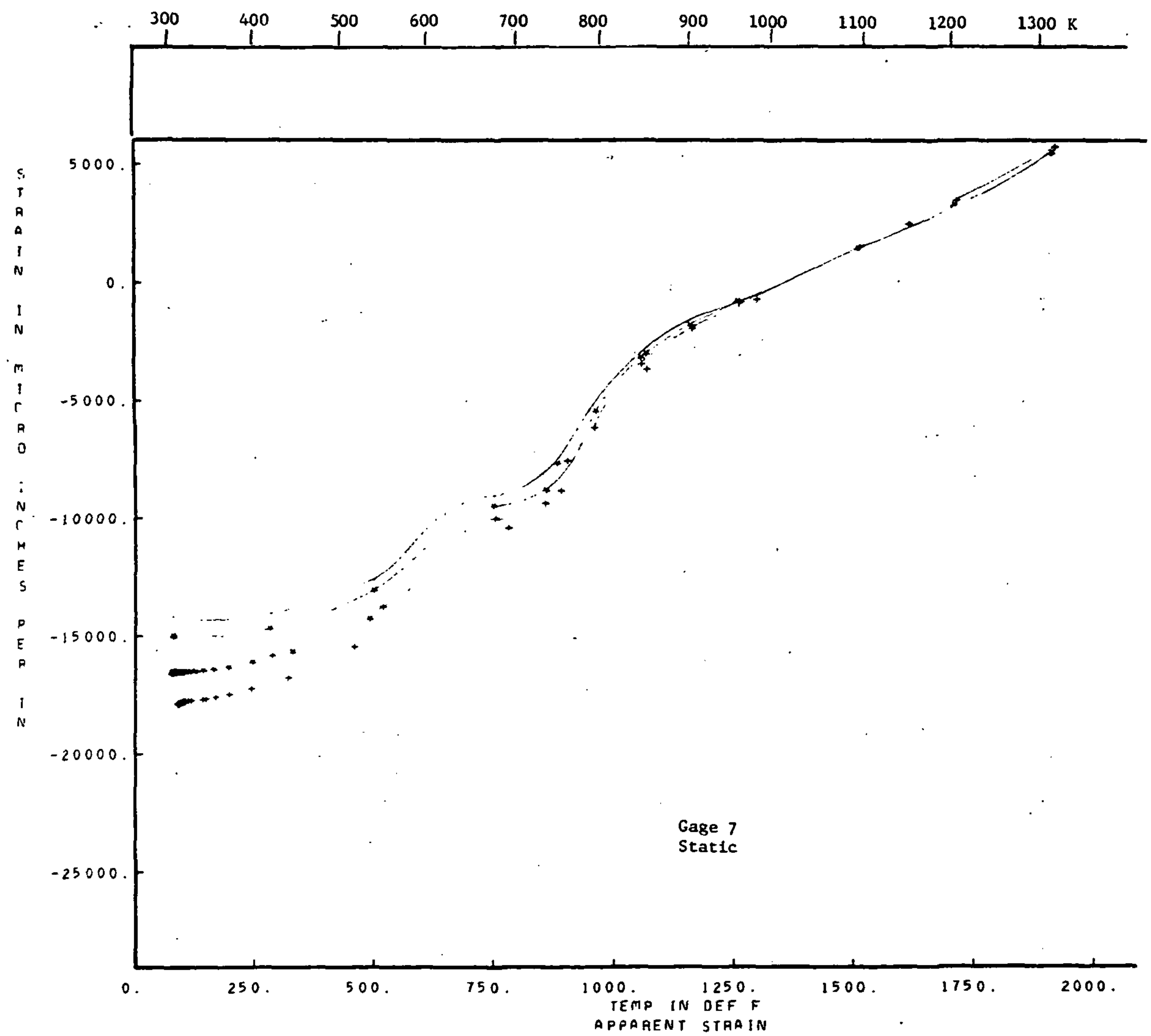
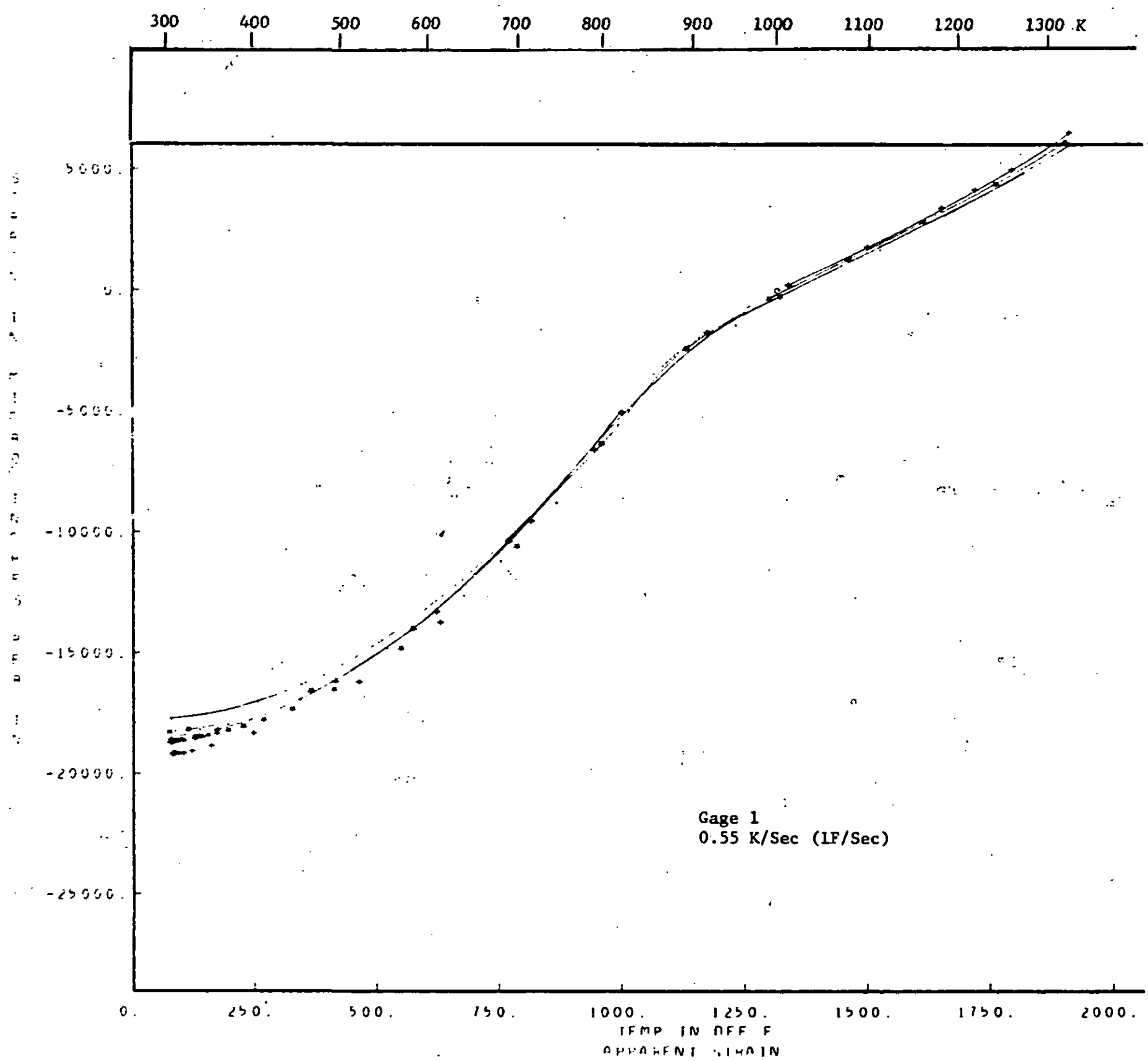
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0. 250. 500. 750. 1000. 1250. 1500. 1750. 2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 3
Static



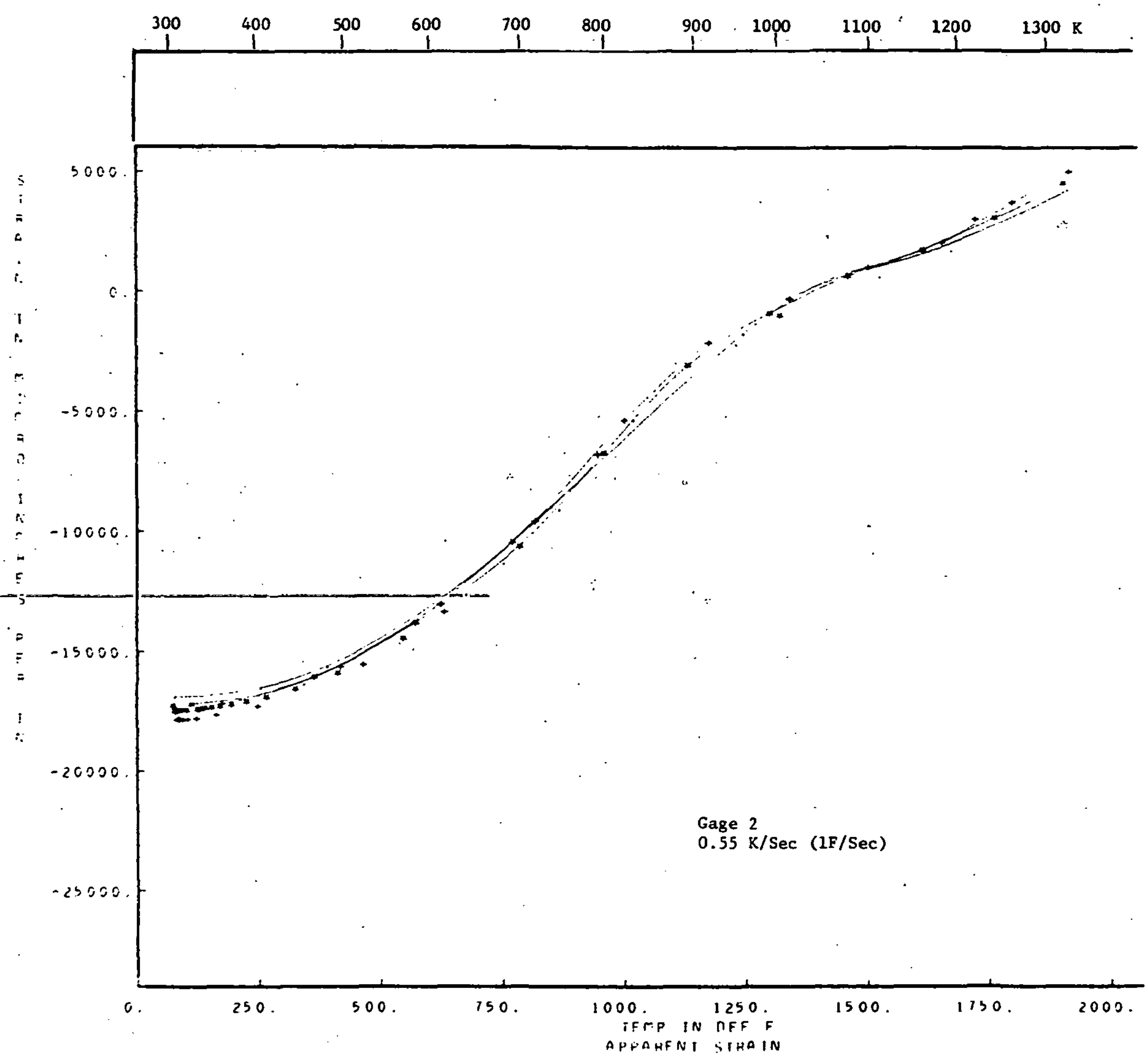
300 400 500 600 700 800 900 1000 1100 1200 1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
0. 250. 500. 750. 1000. 1250. 1500. 1750. 2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 5
Static



300
400
500
600
700
800
900
1000
1100
1200
1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEF F
APPARENT STRAIN
Gage 7
Static



300
400
500
600
700
800
900
1000
1100
1200
1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 1
0.55 K/Sec (1F/Sec)


300
400
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900
1000
1100
1200
1300 K
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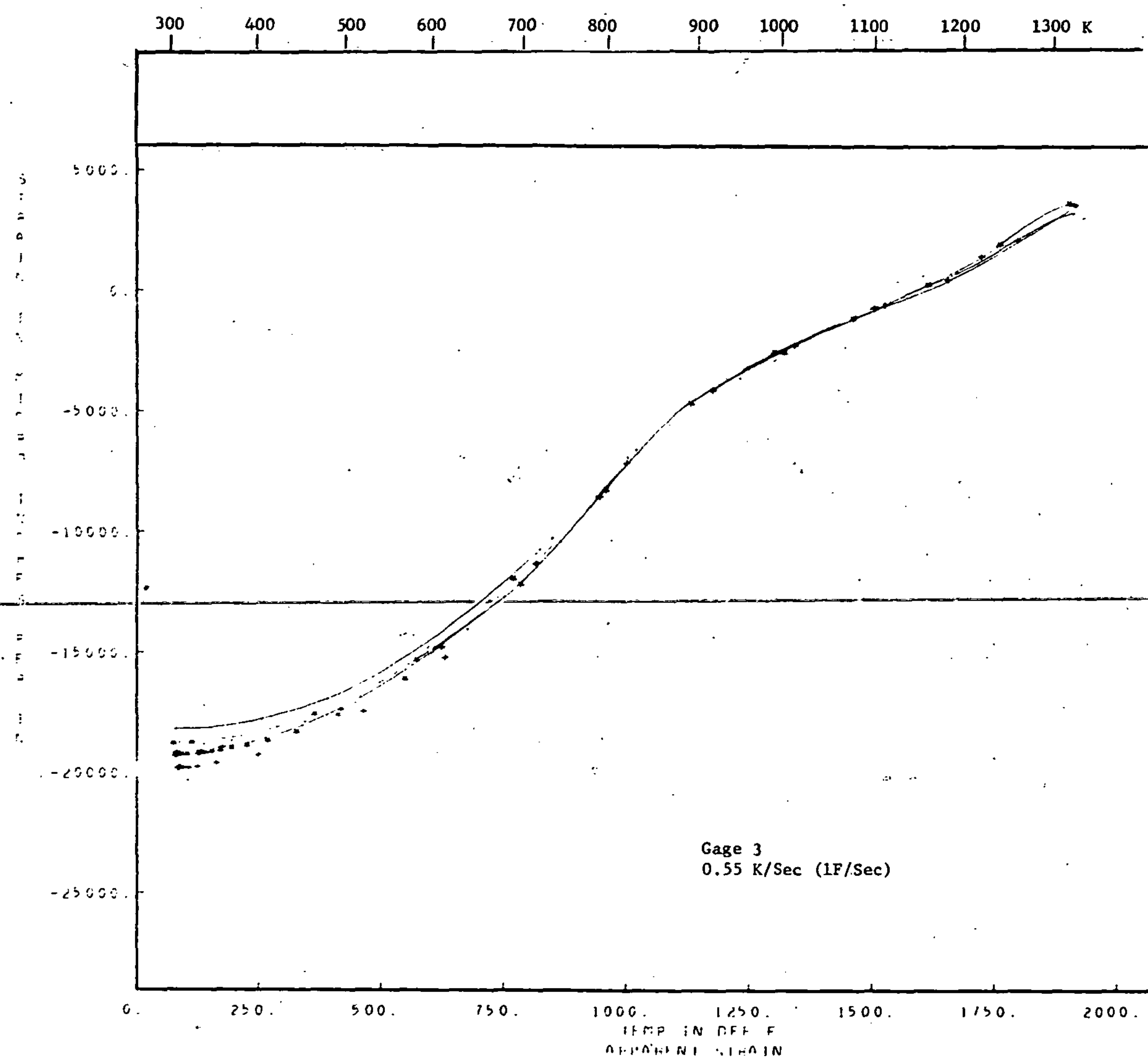
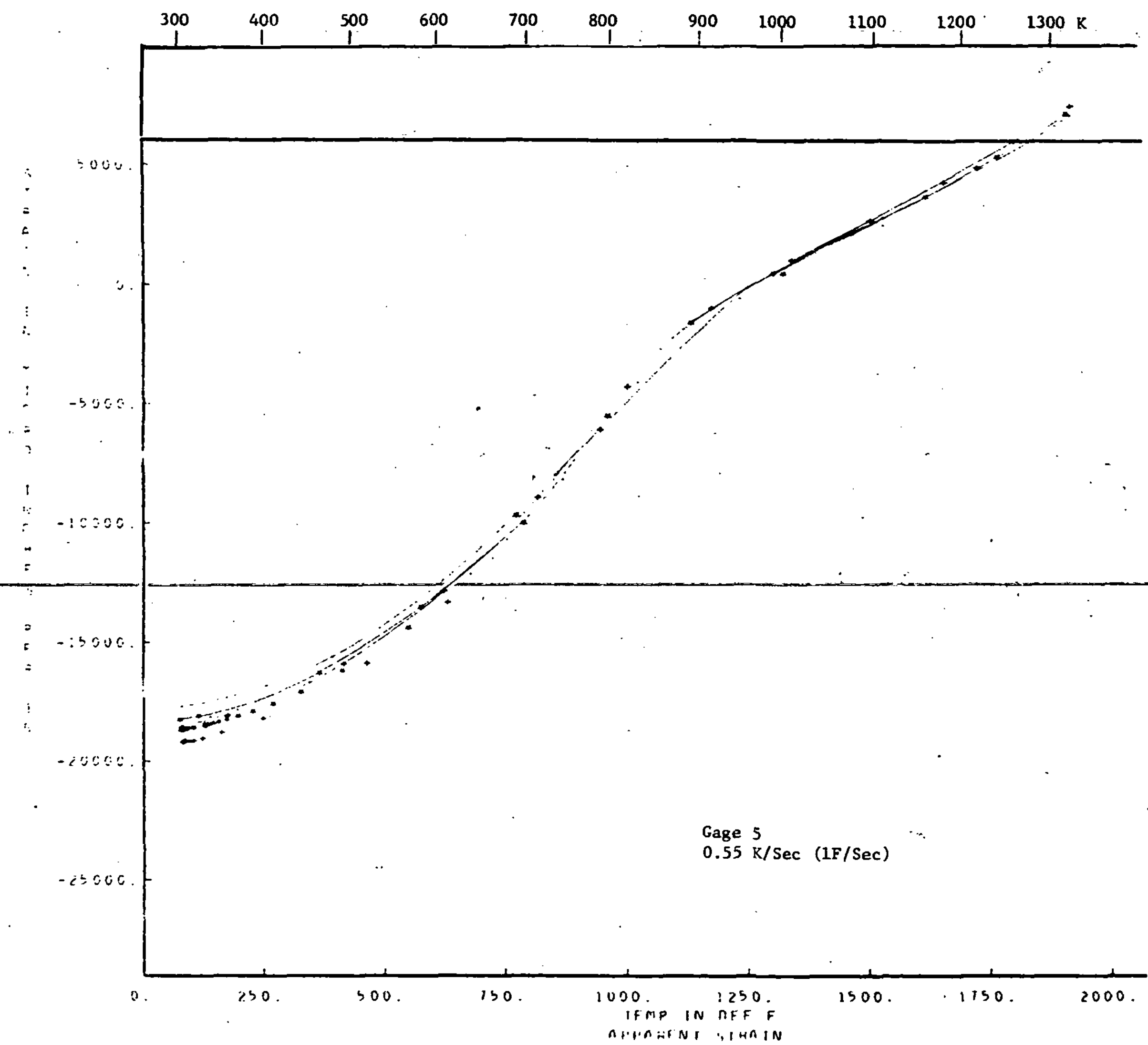
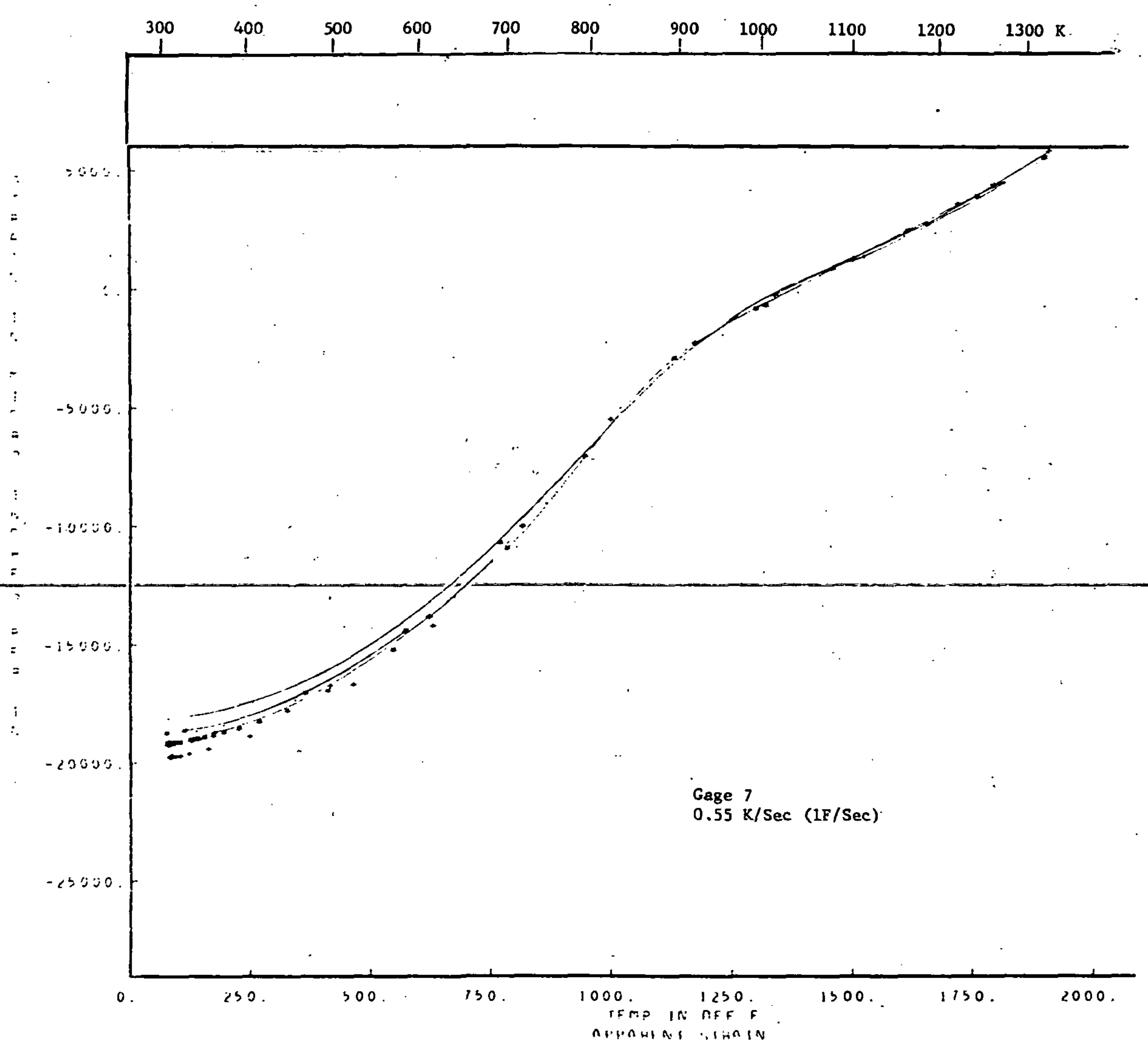
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 2
0.55 K/Sec (1F/Sec)


300
400
500
600
700
800
900
1000
1100
1200
1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
Gage 3
0.55 K/Sec (1F/Sec)


300 400 500 600 700 800 900 1000 1100 1200 1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
0. 250. 500. 750. 1000. 1250. 1500. 1750. 2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 5
0.55 K/Sec (1F/Sec)



300
400
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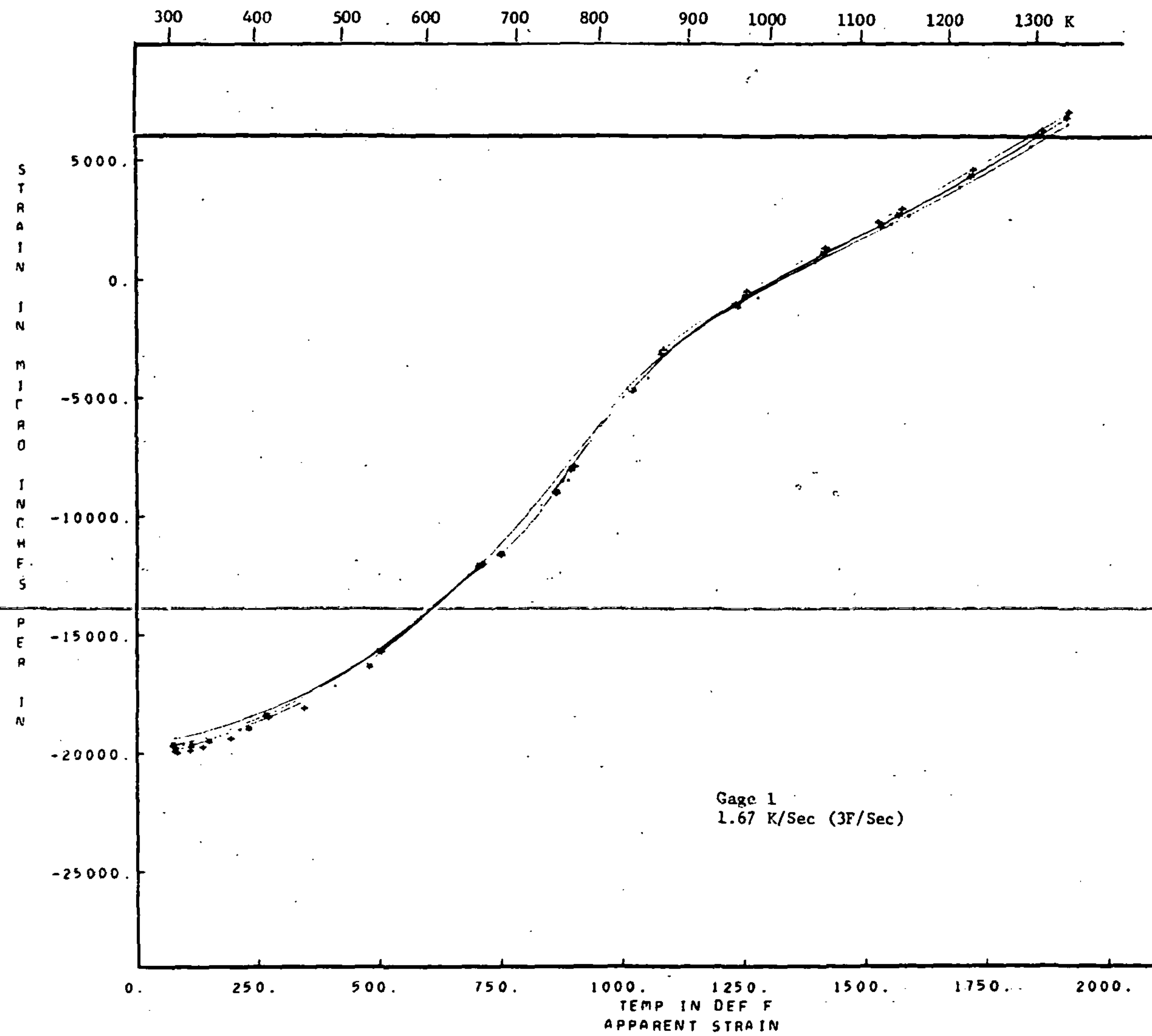
600
700
800
900
1000
1100
1200
1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
Gage 7
0.55 K/Sec (1F/Sec)
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.


300
400
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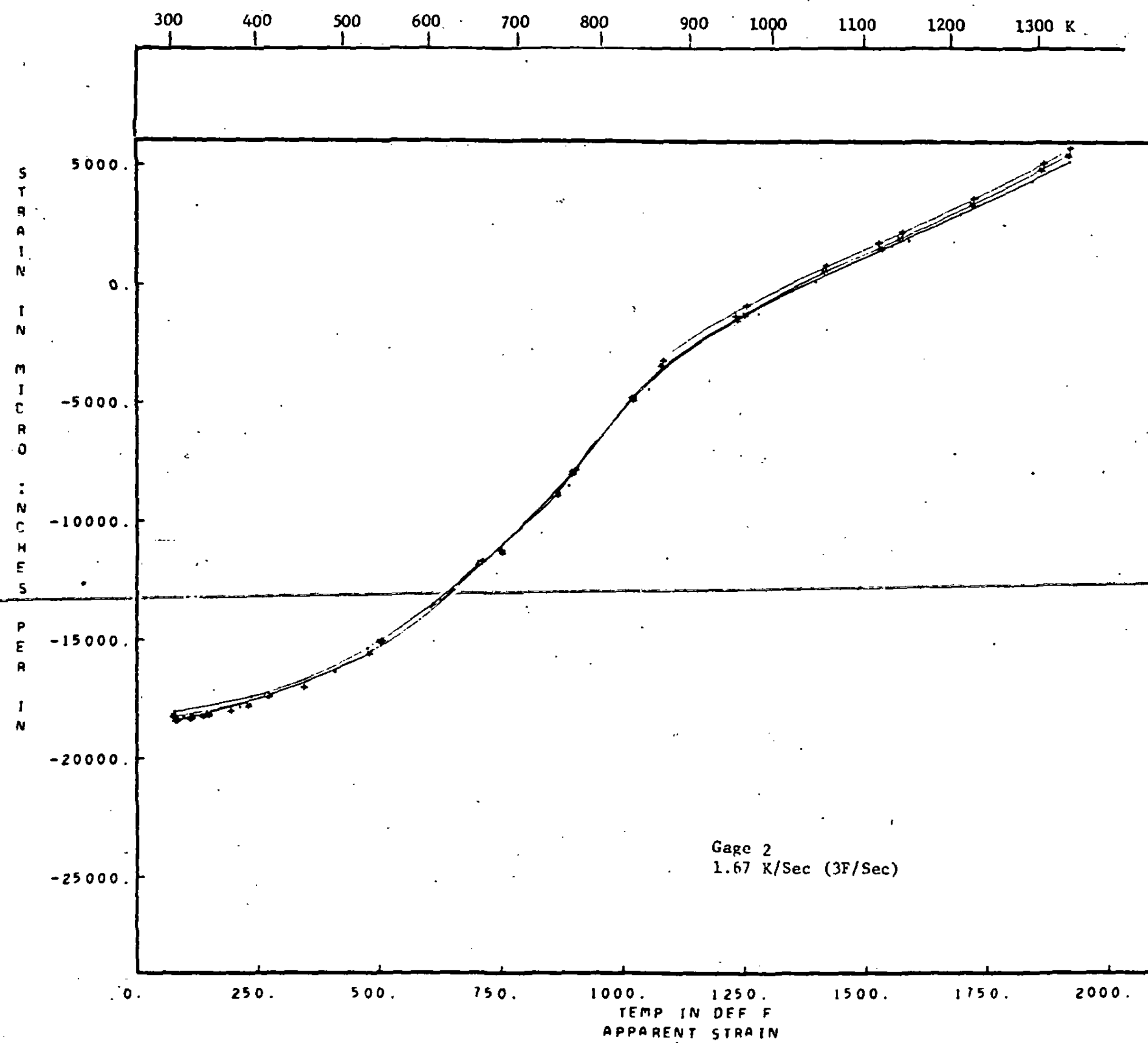
1100
1200
1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEF F
APPARENT STRAIN
Gage 1
1.67 K/Sec (3F/Sec)


300
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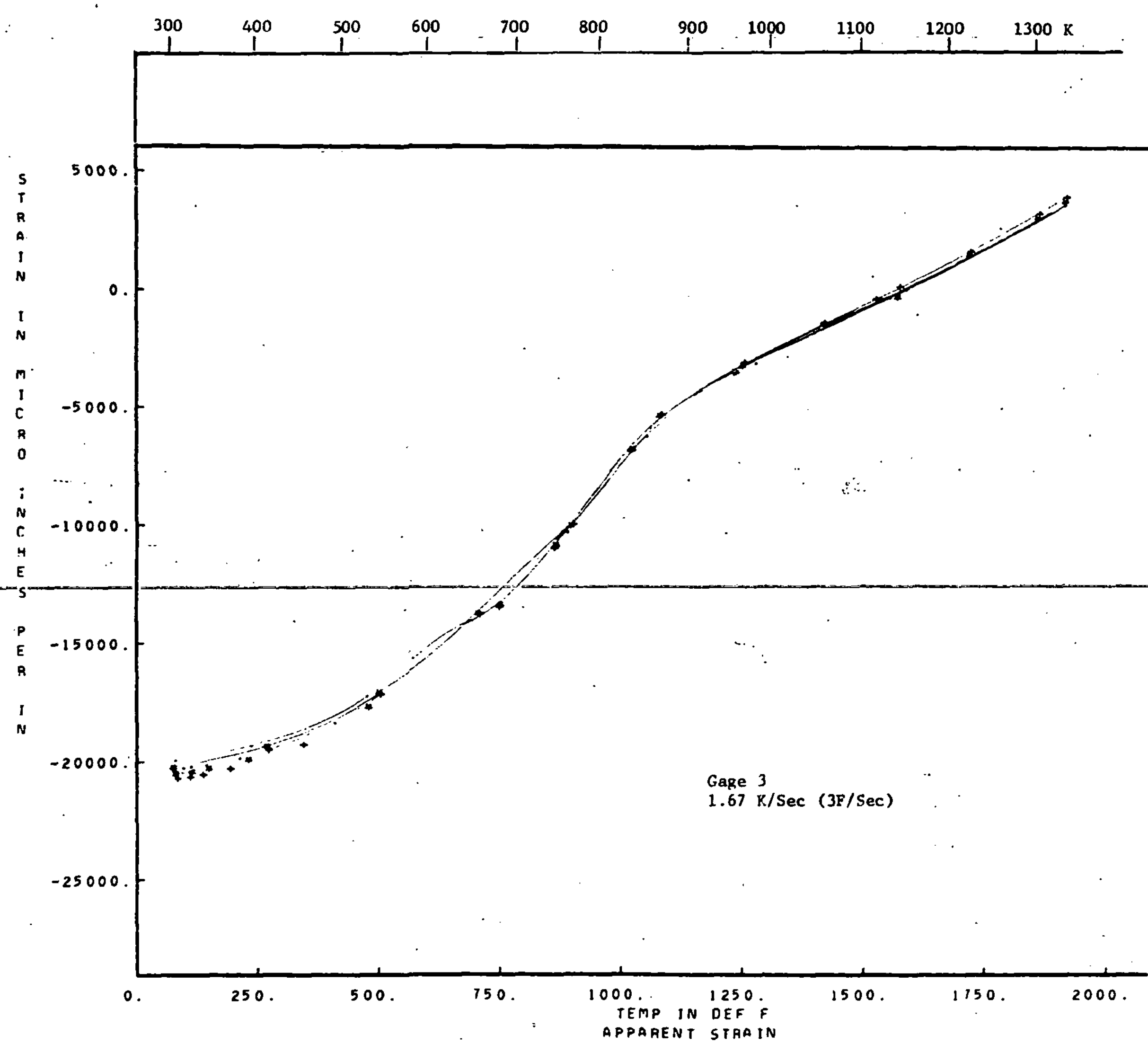
900
1000
1100
1200
1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
Gage 2
1.67 K/Sec (3F/Sec)
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN



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1300 K
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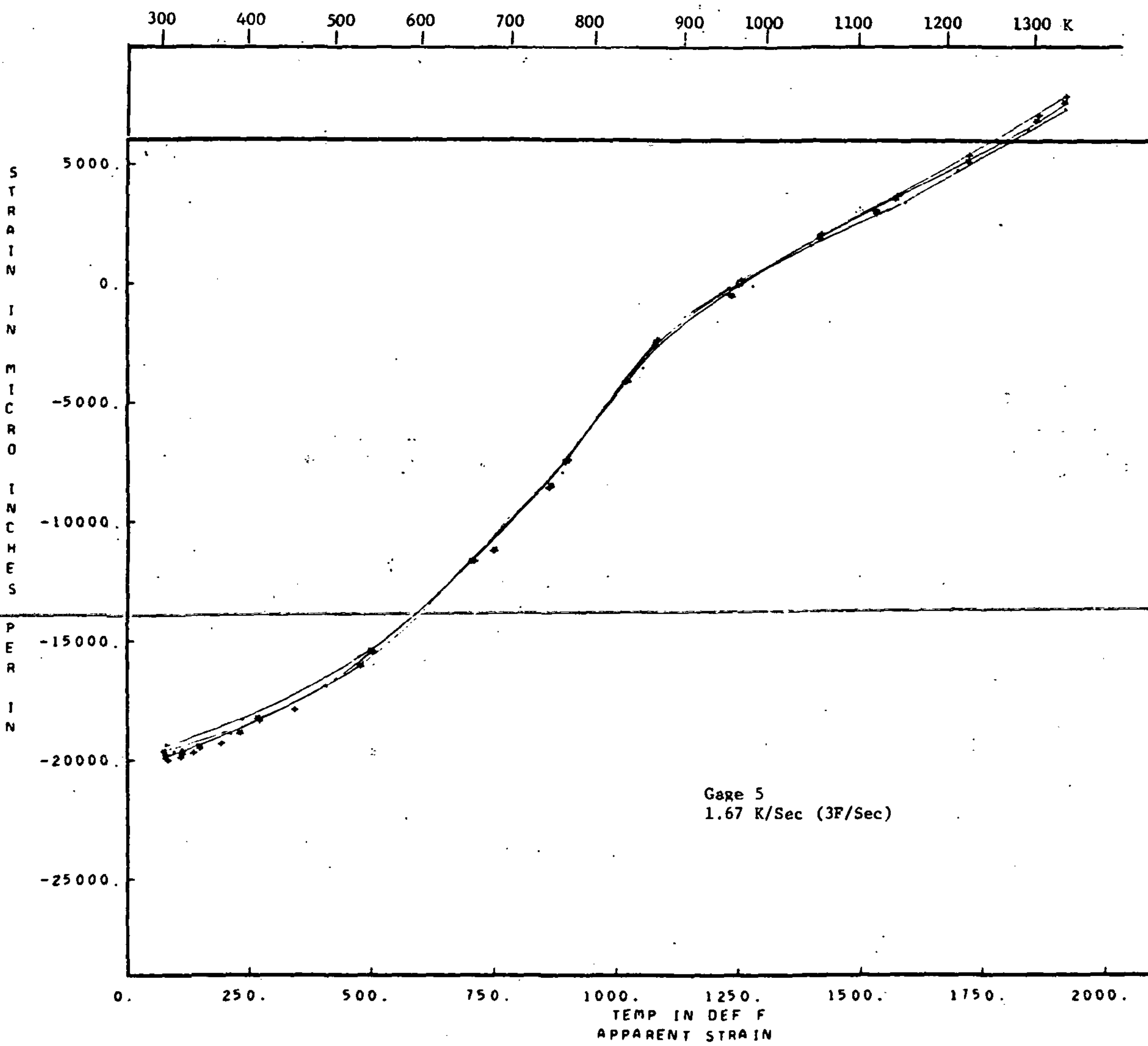
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEF F
APPARENT STRAIN
Gage 3
1.67 K/Sec (3F/Sec)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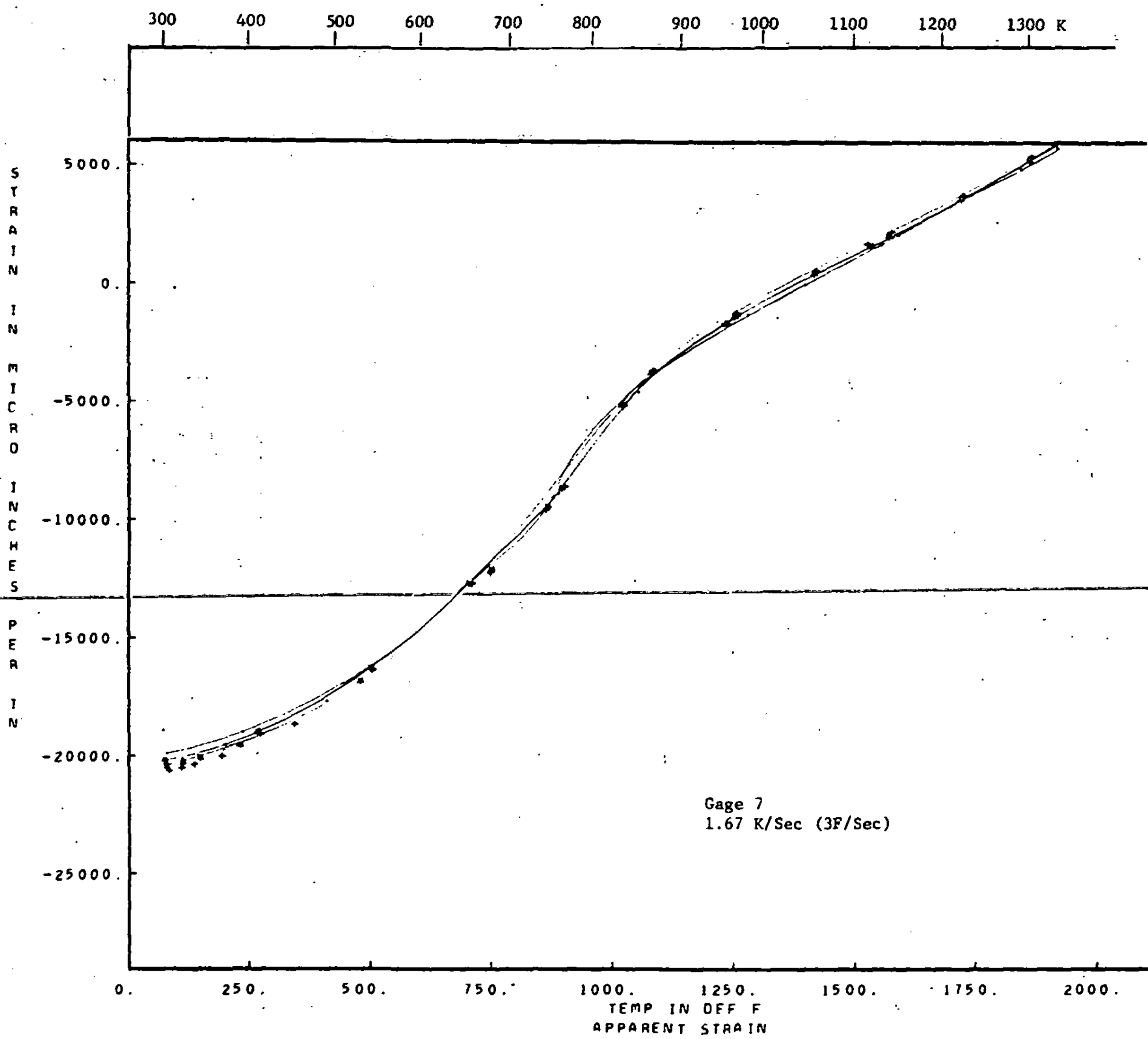
1200
1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
Gage 5
1.67 K/Sec (3F/Sec)
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEF F
APPARENT STRAIN


300
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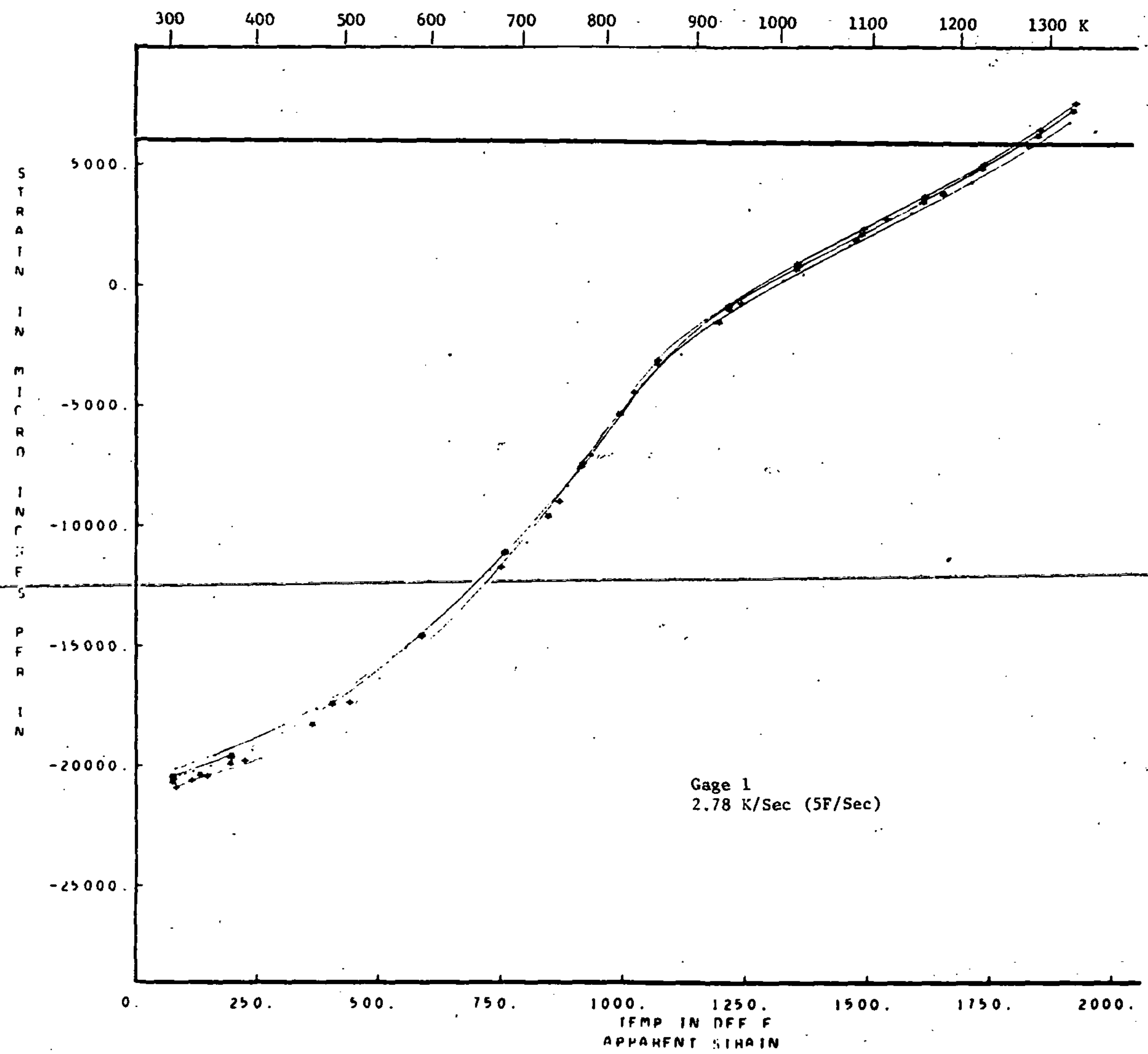
1100
1200
1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
Gage 7
1.67 K/Sec (3F/Sec)
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN



300
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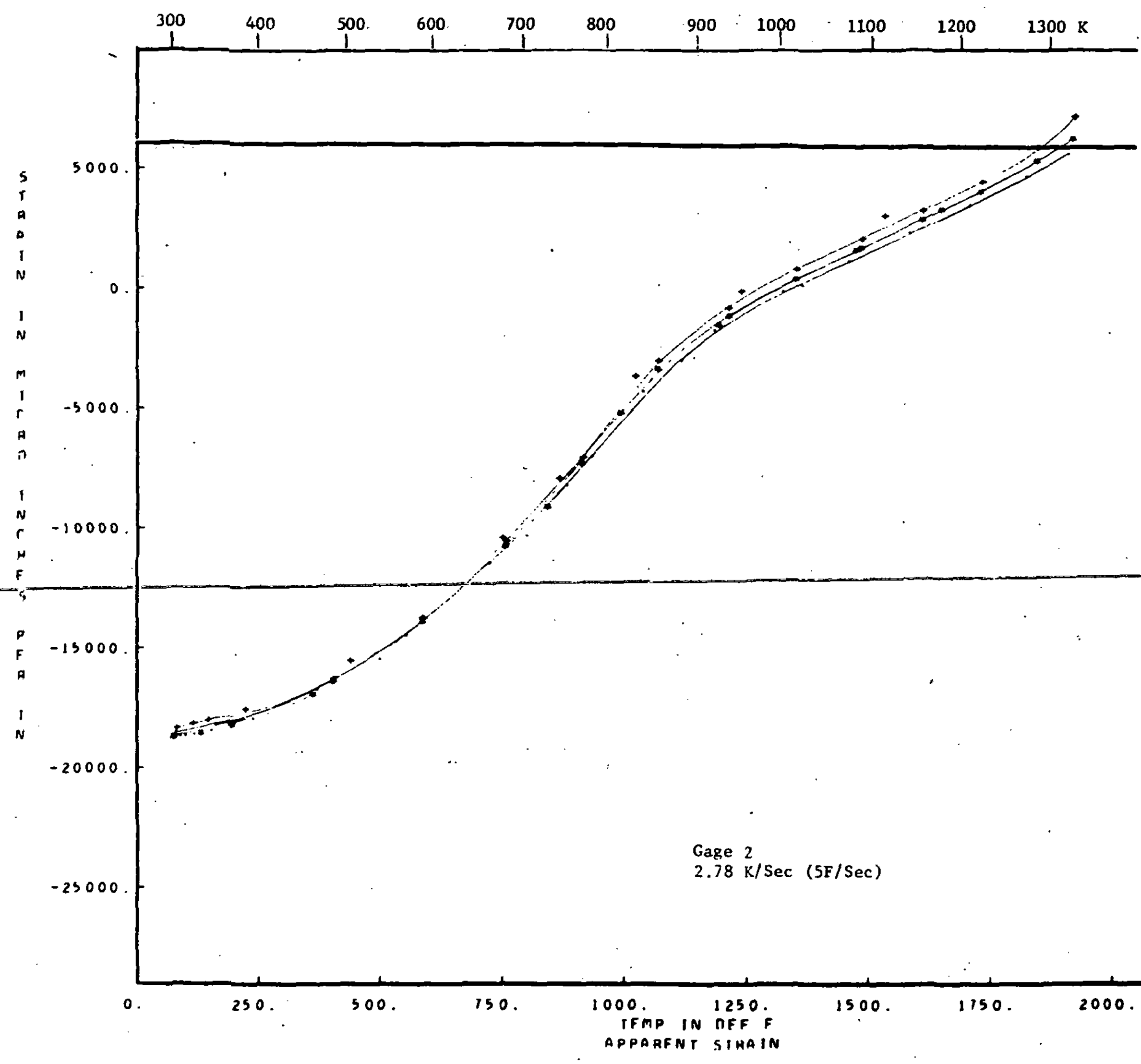
1100
1200
1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 1
2.78 K/Sec (5F/Sec)



300
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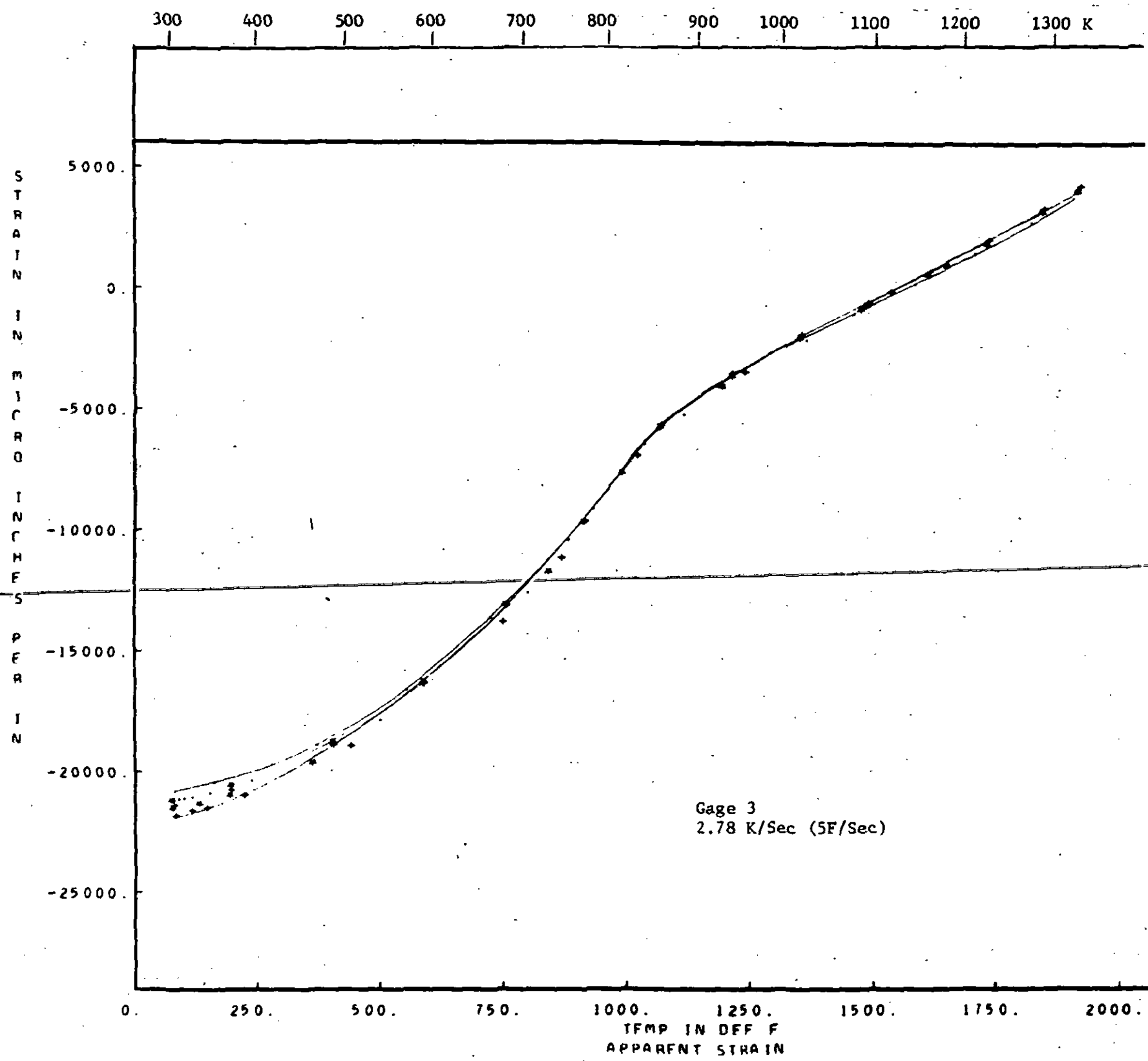
900
1000
1100
1200
1300 K
STRAIN IN MICRO INCHES PER IN
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
Gage 2
2.78 K/Sec (5F/Sec)
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN


300
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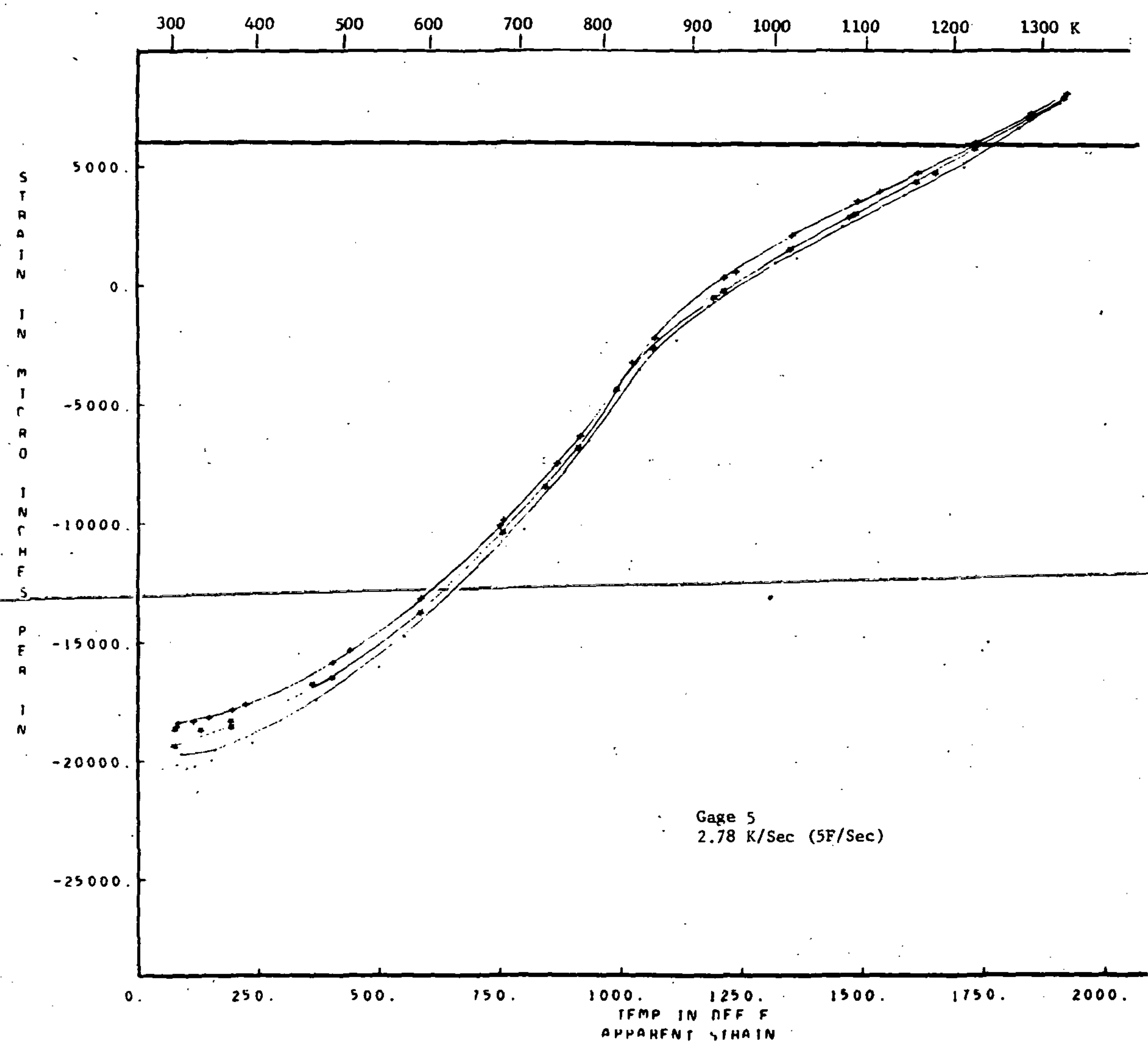
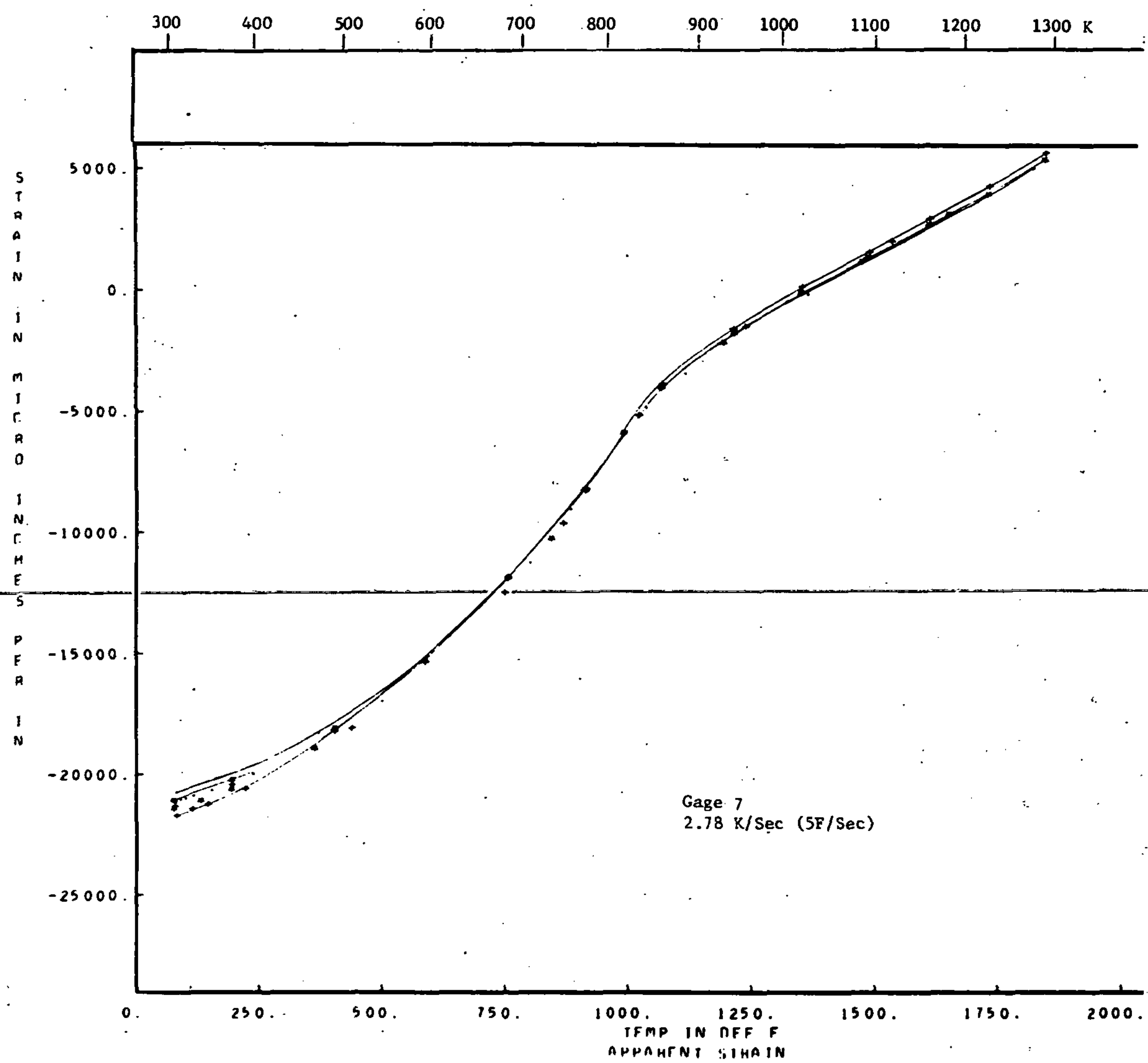
1100
1200
1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 3
2.78 K/Sec (5F/Sec)


300 400 500 600 700 800 900 1000 1100 1200 1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
0. 250. 500. 750. 1000. 1250. 1500. 1750. 2000.
TEMP IN DEG F
APPARENT STRAIN
Gage 5
2.78 K/Sec (5F/Sec)


300 400 500 600 700 800 900 1000 1100 1200 1300 K
5000.
0.
-5000.
-10000.
-15000.
-20000.
-25000.
STRAIN IN MICRO INCHES PER IN
Gage 7
2.78 K/Sec (5F/Sec)
0. 250. 500. 750. 1000. 1250. 1500. 1750. 2000.
TEMP IN DEG F
APPARENT STRAIN